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GROWING PLANTS IN SPACE

by V. P. Dadykin

"Znaniye" Press, Moscow, 1968

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1972

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Translation of "Kosmicheskoye Rasteniyevodstvo"
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For sale by the National Technical Information Service, Springfield, Virginia 22151
$3.00

"Is it possible to grow some kinds of agricultural products on the Moon? What sort of greenhouses with artificial atmospheres would this require and is it possible to use the lunar soil as the ground?"

The answer of Academician M. B. Keldysh is: "I think that, with appropriate adaptations, it is possible. Biologists are seriously occupied with closed regeneration cycles for the growth of plants not only on the Moon, but also in spacecraft. Great advances have already been made in this branch of science."

From the stenographic report of the press conference devoted to the new epoch in the knowledge of the Universe, Pravda, February 11, 1966, No. 42 (17359).

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GROWING PLANTS IN SPACE

V. P. Dadykin[(1)]

ABSTRACT. This book examines possible ways to solve the problems connected with life support systems for cosmonauts on prolonged space flights by using plants from Earth. The cycle of nature on Earth is examined, and methods are proposed for modeling this cycle within a spacecraft. The danger of radiation in space and ways to eliminate it are studied. It is found that in closed, pressurized areas higher plants are quite sensitive to increased oxygen in the air. A 25% concentration of oxygen greatly reduces the intensity of photosynthesis, whereas a concentration below normal stimulates plant growth and intensifies photosynthesis.

Preface

Everyone remembers the days when the conquest of space was initiated. /3* This was October 4, 1957, the date of the first artificial Earth satellite launching, developed and created by Soviet scientists, engineers, and workers. This was also the morning of April 12, 1961 when the first spacecraft was launched with a man onboard, Soviet citizen, Yuriy Gagarin. The space age in the history of mankind had begun. A short time has elapsed since those days, but how many remarkable events have occurred in the development of cosmonautics! Mankind is no longer confined to the advances achieved in mastering space close to Earth, but more bravely and more confidently has gazed at the Moon, at the planets of the solar system, unafraid of the prospect of flights lasting months and years. It stands to reason, however, that these dreams

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*Numbers in the margin indicate pagination in the original foreigh text.

(1) Doctor of Biological Sciences.

are not realized "by a wave of the wand" but that these plans require extensive and purposeful work. Much remains to the done in laboratories, to be tested on short space flights, and only then embodied in the design of long-range spacecraft. The numerous problems of this kind demanding the persistent attention of scientists also include the problem mentioned in the book by V. P. Dadykin. The reader will become acquainted in this book, written in a popular, lively, and interesting style, with the future prospects for a radical solution to the problem of prolonged space flights — the creation in the spacecraft of a closed ecological system — that is, essentially, the conversion of the spacecraft into an autonomous model of our planet with its endless cycles of matter.

Academician V. V. Parin

Introduction

Our generation is extremely lucky. We are contemporaries and witnesses of man's irrepressible breakthrough into space. /4

October 4, 1957, will remain a historic date for centuries. On this day, for the first time, an artificial Soviet satellite was put into Earth orbit.

In less than four years, on April 12, 1961, Soviet citizen, Yuriy Aleksandrovich Gagarin, in the "Vostok" spacecraft — built by Soviet scientists, engineers, and workers — left the Earth and performed a space flight. This epoch-making event signifies the beginning of an era of man's egress to the vast reaches of space.

The storming of space continues. New spacecraft are being launched; more and more complex scientific and technical problems are being solved.

The advances made in mastering space have been so significant that the question of space flights to the Moon, around the Moon, to planets, and subsequently landing men on the Moon and the planets has become real.

Launchings of spacecraft and manned flights into space have expanded our knowledge of space close to Earth to an extraordinary degree, and have led to the solution and practical verification of many technical problems connected with placing spacecraft into a designated flight trajectory, and other problems of space navigation. Soft landings in designated areas by spacecraft have been mastered. In February 1966, there was a brilliant execution of a soft landing by the spacecraft "Luna-9", in December 1967, by "Luna-13", and on October 18, by the automatic station "Venera-4".

For successful manned flights into space, it was necessary to create not only reliable systems for the control and the return of the spacecraft and reliable communication lines and telemetry information, but also to provide in the spacecraft cabins normal conditions for human life (specific temperature, humidity of air, its composition and pressure). A particularly crucial /5 and difficult problem is the maintenance of the gas composition of the atmosphere in the spacecraft cabin within the range permissible for man.

During breathing over a 24-hour period, a man consumes about 650 l of oxygen and expels about 550 l of carbon dioxide. It is necessary to regenerate the air continuously by removing the accumulated carbon dioxide and replenishing the consumed oxygen.

Our designers built a reliable system of air regeneration operating on chemically active substances absorbing carbon dioxide and liberating oxygen.

However, an increase in the duration of space flights requires an increase in the supplies of chemically active substances for the regeneration of the air. Undoubtedly, in the very near future, the volume and weight of these substances will lead to an irreconcilable contradiction with respect to the dimensions of the spacecraft cabin.

K. E. Tsiolkovskiy supported in his time the concept of creating aboard the spacecraft an artificial microworld which would produce cycles of matter similar to those occurring under natural conditions on Earth: "People will contaminate the air and eat the fruit, and plants will purify the air and produce the fruit. Man will return in full measure what he stole from the plants: in the form of fertilizers for soil and air".

In addition to the flights, it is necessary to create in space normal conditions for man's life on the Moon and the planets. It is known that the Moon and also one of the planets nearest the Earth, i.e., Mars, are practically devoid of an atmosphere and that the temperature conditions on these bodies are far from "the comfort zone" as understood on Earth. Consequently, it is necessary to build life-support systems on lunar and planetary stations. In this case, plants can successfully perform the work of regenerating air, water, and food. Furthermore, the provision of planetary stations for life-support systems obviates a number of limitations existing in spacecraft cabins (limited volume, weight, absence of gravitation).

The transition from ideas expressed more than half a century ago to their practical application is still very remote. With the first attempts to calculate such a system, many difficult and still obscure problems have been revealed.

This book examines possible ways and means for the solution of problems connected with the vital processes of cosmonauts on prolonged space flights by the use of terrestrial plants. It will be noted, by the way, that the problems of creating closed artificial systems for the cycles of matter are of practical importance, not only on space trips and planetary stations. Such systems will find application also under terrestrial conditions — for example, to increase the autonomy and duration of submarine navigation and in other ways.

The Founders of Space Navigation on Plant-Growing in the Cosmos /6

In examining the present state of the problem of plant-growing in space, it is natural that we recall briefly how the solution appeared to the founders of space navigation.

In his work, K. E. Tsiolkovskiy, using contemporary data of biological and other related sciences, made the first calculations of plant productivity and determined the dimensions of the space required to cultivate plants in a spacecraft. He calculated that per 1 m^2 of surface which is normal (perpendicular) to the incidence of solar rays there are 43.2 kcal daily. Plants, however, are capable of utilizing up to 5% of the solar energy, that is, 2160 cal daily. Using thermochemical data on the calorific ability of various products of vegetable origin, K. E. Tsiolkovskiy determined that the daily supply of potential energy on one meter of area illuminated by the Sun is equivalent to 0.5 kg of flour, or 4 kg of carrots, or 5 kg of cabbage, or 0.6 kg of sugar, or more than 0.5 g of rice.

Turning to tropical agriculture, K. E. Tsiolkovskiy writes that one hectare of a banana plantation yields up to 25,000 poods of bananas corresponding to 0.11 kg per day on one square meter of area. But if we consider that the Earth is covered by clouds and a thick layer of air and water vapor, that night comes and that the solar rays fall obliquely, that the amount of carbon dioxide is considerably less than optimal, and that the methods of cultivation in the tropics are very primitive, then "one must at least increase tenfold the gifts of the Sun and assume the productivity of one square meter in our artificial garden to be not less than 1.1 kilogram of bananas."

The general conclusions from the calculations by K. E. Tsiolkovskiy are that: "One square meter of a greenhouse, facing the sunlight, is sufficient for the nourishment of one person."

However, this conclusion is theoretical. Feeling this, K. E. Tsiolkovskiy continues: "... who prevents us from having a greenhouse with an immense surface in a packed state, that is, in a small volume!... We assemble in and remove from the rocket our hermetically sealed cylindrical boxes with various sprouts and suitable soil."

The discussions by K. E. Tsiolkovskiy on the life of plants in the absence of gravitation are of unquestionable interest. "Neither plants nor people will feel gravity and, for several reasons, this can be very advantageous. Plants will not need thick trunks and branches which frequently break from the abundance of fruit and constitute useless ballast for trees, shrubs, and even grasses. Nor does gravitation interfere with the rising of sap. *Still, a little gravity can be useful to plants:* to keep soil and water in one place and, in general, to maintain order." In another place, he raises the question: Where will a plant grow in the absence of the force of gravity? And he himself attempts to answer: "In all probability, its direction will be a matter of chance and the influence of light." /7

K. E. Tsiolkovskiy sees clearly that these are theoretical constructions, and the calculations must be verified and confirmed in experiments carried out on Earth. "In addition, it is entirely possible to develop and test practical methods for man's respiration and nutrition in isolated space". He outlines a program of investigations on the Earth preceding flights into space: To determine the smallest surface illuminated by solar rays which is adequate for man with respect to respiration and nutrition; it is possible to find and test plants suitable for this purpose." In another place, we find indications of the necessity to investigate the light regime in space cultivation, ways to combat pests, plant diseases, and others.

And now, more than half a century after K. E. Tsiolkovskiy saw the forthcoming space travel with astonishing clarity, one is amazed at the exceptional insight of his mind.

With surprising precision, he also determined his role and place in the greatest problem of the egress of man into space: "First these inevitably arise: thought, fantasy, tales. Scientific calculation follows them. And then finally fulfillment crowns the thought. My works on space travels belong to the middle phase of creation". And further: "I think of playing the role of a choirmaster." "People more knowledgeable and stronger will solve the problems presented by me, and more knowledgeable and experienced technicians will help to create the spacecraft itself."

Assume today we have the resources to determine and to calculate more accurately the dimensions of the necessary space garden, and assume we at present know far more about man's nutritional requirements. Even if some of the discussions of K. E. Tsiolkovskiy appear to be somewhat naive, and our figures essentially differ from those used by him, nevertheless, the greatness of his idea, his general concepts and basic methodical approach — i.e., studying the data on solar energy and on man's requirements for life — remains a stable, solid approach. K. E. Tsiolkovskiy became the actual choirmaster in the mastery of space with respect to the problems of space plant-growing.

Alongside the name of Tsiolkovskiy, there will also remain in the history of science the name of his follower and friend, versatile researcher and /8
talented engineer, Friedrikh Arturovich Tsander, for his important contribution to the theoretical problems of astronautics. He contributed a great deal to the establishment of theoretical principles for designing jet engines. At the same time, F. A. Tsander is an eminent practical engineer. He carried out many investigations in the search for high-powered solid fuel for rockets. He designed and built the first jet engines, and he worked out a number of other problems.

Sharing the idea of K. E. Tsiolkovskiy on the utilization of terrestrial plants for life-support conditions during protracted space travels, F. A. Tsander methodically performed investigations on the growth of vegetables in greenhouses where, instead of soil, charcoal was used with human excrement serving as fertilizer.

As far back as 1926, F. A. Tsander conceived of writing and publishing a book under the name "Flights to Other Planets; First Step into Boundless World of Space". To our regret, this book remained unwritten. In the archives was only an extensive table of contents (summary) of the projected work. The eleventh incomplete chapter of this book bears the heading, "Greenhouses as Light as Airplanes and a Cyclic Process to Support Life Under Hermetically Sealed Conditions on an Interplanetary Spacecraft, on an Interplanetary Station, on the Moon, and on Other Planets Possessing an Atmosphere."

The contemplated contents of this chapter are so interesting that we consider it our duty to give it in its entirety:

"1. The amount of oxygen needed for breathing, the amount of exhaled carbon dioxide; obtaining oxygen from the greenhouse, utilization of carbon dioxide for the greenhouse. Designs for separating and connecting the greenhouse and the living quarters.

2. Amount and composition of daily food requirements.

3. Growth of plants in pure oxygen and

a) in fertilized crushed charcoal;

b) in nutritive liquid;

c) in space, in which a nutritive liquid is sprayed;

d) in cases when the nutritive liquid is supplied to the roots with a dropper.

4. Preparation of fertilizer and nutritive solution; application of the sewage aeration method. /9

5. Experiments carried out up to the present.

6. First experiments performed by the author.

7. Constructions and calculation for airproof clothing.

8. Utilization of waste matter for feeding birds, fish, and animals."

Thus, the founders of rocket technology and space navigation gave us not only the theory for building interplanetary spacecrafts and the theory of calculating interplanetary travels, but also laid the foundation for a practical solution to the most important problems of the life-support of man during protracted space travel or during a stay on other planets.

A Little About the Scale of Space

In order to elucidate the advisability of building areas for growing plants on the spacecraft, we would remind the reader of some data on the distances which spacecraft have to travel and the velocities which have to be developed on space flights and, as a result of this, the duration of space travels.

The solar system consists of nine planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto (Figure 1).

After man has landed on the nearest celestial body — the Moon — flights /10
will be made to more distant planets and celestial bodies having larger dimensions — to Mars or Venus. It must be noted that there is a basis for assuming the presence of life on Mars.

At the most favorable time, the distance from the Earth to Mars is 80 million km., and to Venus — 40 million km.

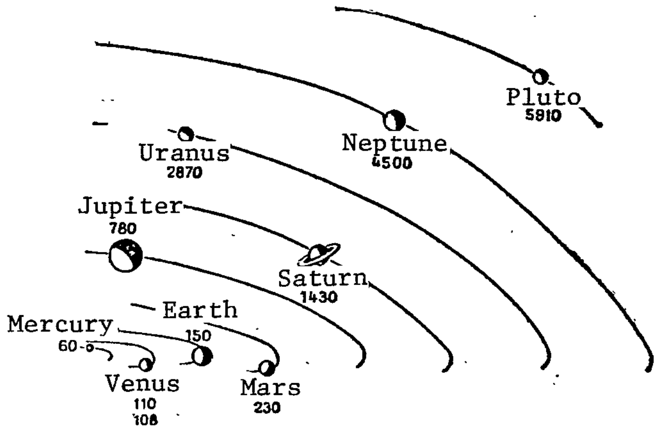

Figure 1. Arrangement of orbits in the movement of planets of the solar system. Figures indicate the average distances from the Sun in millions of kilometers.

Thus, tens and hundreds of millions of kilometers are the distances the spacecrafts have to travel to reach the neighboring planets.

Which velocities are to be given to the spacecrafts launched in order for them to reach their final goal — the neighboring planets? In cosmonautics, as is generally known, three space velocities are distinguished: the first, second, and third. The first space velocity (sometimes called circular) is equal to 7.2 km/sec. At such a velocity, the launched rocket will travel in a circular orbit around the Earth due to the balancing of the force of terrestrial gravity (force of weight) and the centrifugal force. With an increase in the initial velocity, the orbit of the spacecraft begins to expand, and changes from a circular to an elliptical orbit. At an initial velocity of 11.2 km/sec (second space velocity) the flight trajectory changes from a closed figure — an ellipse — to an open hyperbola, and the rocket will leave the sphere of primary influence of terrestrial gravity.

Leaving the sphere of primary influence of the Earth's gravity, the spacecraft will either enter the sphere of the Sun's gravitational effect, and then become its satellite, or will fall under the influence of the primary gravitational forces of some other planet, and will then approach it.

At the rocket's initial velocity of 16.7 km/sec (third space velocity) it will escape from the action of solar gravity, and will leave the solar system forever.

Specialists have calculated that for a successful flight to Mars the spacecraft must be accelerated up to 11.5-11.7 km/sec. For a flight to Venus, the speed must be not less than 11.5 km/sec. Travel to these planets in the most advantageous trajectory (in terms of a minimal consumption of fuel) will take about 300 days to Mars, and 130-140 days to Venus.

A simple arithmetic calculation shows that providing the cosmonauts with all the requirements essential to life (air, food, and water) by using supplies taken from the Earth is a highly complex matter. First, the required reserves of air, water, and food for such prolonged travels are very heavy. Second, they require large storage facilities on board the spacecraft. Third, /11 not all food products can be preserved during a protracted flight. Fourth, the packing of the products, reserves of water and air (assuming cylinders with compressed oxygen) is a useless load whose lifting into space requires a large amount of energy. We must recall that for launching the satellite with Yu. A. Gagarin (weight of spacecraft without the last stage of the rocket-carrier, 4725 kg) six engines were operating at a total capacity of 20 million hp, or more than 4200 hp per each kilogram of useful load. Finally, no matter how large the reserves on board the spacecraft, they are not infinite. In the case of a delay in space, a shortage of supplies would have a disastrous effect. These considerations compel us to look for new ways of providing cosmonauts with the required food, air, and water during prolonged interplanetary travels.

Several methods for the regeneration of water and air on board the spacecraft using physicochemical procedures have been suggested, discussed and experimentally verified. However, physicochemical methods of regenerating water and air require stocks of reagents which also have weight and occupy space. In addition, if the system for regenerating water and air is based on the application of some substances kept in stock, the use of such a system would always limit the time of the space journey. Consequently, the unforeseen prolongation of the voyage is fraught with serious consequences. In addition, physicochemical methods for regenerating water and air require considerable amounts of energy which at present is extremely diffcult to provide. It can be surmised that, until an airborne atomic electric power station is installed, it is doubtful whether physicochemical methods could be successfully utilized to a full extent.

All the above suggests that the most reliable method for providing cosmonauts with air, water, and food would be cultivation of autotrophic plant organisms.

Plants absorb carbon dioxide from the air, and liberate oxygen. During the transpiration process, they evaporate a significant amount of water of a quality nearly equivalent to that of distilled water. By using processed products of man's biological functions, plants will recreate food for the cosmonauts.

Recently, in a number of foreign publications, reports have appeared on building nuclear engines for spacecrafts in the near future. With that kind of energy installation, one could anticipate the development of space speeds of the order of 30-45 km/sec. Thus, the time for the flight to the nearest planets would be shortened by nearly one order of magnitude. For /12
example, instead of 130 days to Venus, it could be reached in 13-15 days. Travel to Mars would take 30-35 days, instead of 300 days.

As such speeds it hardly would be expedient to equip the spacecraft with a system for the regeneration of air, water, and food by using plants. It is obvious that for 30-50 days the required stock would be used without any difficulty.

However, the necessity of building a system using plants for the life-support of man still exists in this case, since plants are needed on planetary stations. It is true that on the planets, as compared with the spacecraft, the conditions for building and operating cultivation rooms are different: the question concerning the rigid requirements for weight and dimensions no longer arises, because weightlessness disappears. All the other problems remain complex. However, the building of atomic engines for cosmic flights is still remote. Meanwhile, we shall investigate:

What Does a Man Need for Life and Work?

Any physiological process in the human organism (also in animals), whether it is breathing, the operation of the heart, peristalsis of the intestinal tract or any other process requires the consumption of a definite amount of energy. The energy consumed by the human organism in a fully resting position is called basal metabolism.

The energy consumption by the organism is uusally expressed in calories. The consumption of energy for basal metabolism is subject to deviations. There are many reasons for the deviations: the state of the nervous system, the activity of the endocrine and enzymatic systems, and many other systems. On the average, for a healthy male, 25-30 years old and of 65-70 kg weight, the value of basal metabolism is 1700 kcal daily. Intake of food increases the consumption of energy by 10-15%.

Various kinds of activity — the operation of muscles, mental and physical work requiring large exertion — increase the consumption of energy by the organism. The energy consumption increases with the difficulty of the work. It is considered that the daily consumption of energy by man in mental or physical work of average exertion is about 3000 kcal.

We should recall that K. E. Tsiolkovskiy, using the data available to him at that time, determined that the daily consumption of energy by man setting out for space travel was 3000 kcal. Lately, information has been obtained indicating that for a prolonged space flight man requires a smaller amount of energy. The amounts of energy required for cosmonauts are determined as 2800, 2500, and even 2200 kcal daily. /13

The energy for a man's vital activity is supplied by food. In any organism, continuous processes occur with the biological oxidation of carbohydrates, fats, and proteins found in food. Oxidation most frequently yields carbon dioxide and water, and the released energy is used by the organism for the formation of high energy compounds, mainly, adenosine triphosphate (ATP). Part of the energy is converted to heat and is dissipated.

The energy accumulated in ATP and other high energy compounds is transferred in a complex way (as yet not clarified) to those parts of the organism where it is needed and used for various physiological processes.

Proteins, fats, and carbohydrates constitute the basic nutrients of man. Most wholesome food should include the necessary amounts of amino acids, vitamins, and mineral substances.

The requirement of the human organism for protein is determined by the intensity of the processes in the organism with the restoration of tissues. It depends on the age, growth, sex, individual characteristics of the organism, and also on the activity of man. It is considered that, on the average, a man can limit himself to a norm of 1.1-1.3 g of protein per kilogram of body weight. Consequently, a man of 70 kg weight must take in 80-100 g protein.

It is known that some amino acids cannot be synthesized in the organism. They have to be introduced in a finished state with food. The organism utilizes the amino acids introduced with food for the formation of various proteins, enzymes, hormones, and other substances. Amino acids which are not produced by the organism are termed indispensable. These include: methionine, lysine, tryptophan, phenylalanine, leucine, isoleucine, threonine, and valine.

The indispensable amino acids, in addition to participation in the synthesis of proteins, play an important role in a number of physiological processes of the organism. Thus, lysine, tryptophan, and arginine participate in the growth process, while phenylalanine provides normal operation of the thyroid, adrenal, and other glands.

According to modern concepts, the daily requirement for indispensable amino acids in the human organism is 31 g.

Fats, like proteins, are a necessary component of the diet of man. They are components of all parts and tissues of man, and they represent an important energy source. Ordinarily, fats are divided into two categories: protoplasmatic, which are components of cellular structure, and reserve fats which /14
are put aside by the organism and mobilized by the latter when necessary.

Fats of various origins differ from each other in terms of quality and physiological action. Their main difference is attributed to the properties of the fatty acids in their composition. Fats of animal origin contain mainly saturated fatty acids: stearic, palmitic, lactic, and others. Fats of vegetable origin contain unsaturated fatty acids which have double bonds between the adjacent carbon atoms. Among the unsaturated fatty acids, the most frequently found are: oleic, linoleic, linolenic, and other acids.

Unsaturated fatty acids play an important role in the fat metabolism of the organism, in the preservation of the elasticity of the blood vessels, and in the decrease of blood vessel permeability.

According to modern scientific concepts on nutrition, a man must take in 80-100 g of fats daily. In terms of calories, this is about 30% of the daily quota for man.

In addition to their importance as far as energy and metabolism are concerned, fats are also important since they contain a number of substances which fulfill an important biological role in the organism. Among such substances, the group of phosphatides should be noted. Phosphatides are present in all cells of the organism. They ensure the cellular metabolism processes and maintain the permeability of the cellular membranes on the proper level. The fats also contain various sterols, which normalize the cholesterol metabolism and act as a prophylactic medium against arteriosclerosis. They also contain other substances in the absence of which the organism is subjected to a number of disorders.

The main source of energy in man's diet are carbohydrates. Not less than half of the calories in food are secured at the expense of carbohydrates. A significant part of the carbohydrates introduced into the organism undergoes rapid oxidation to carbon dioxide and water with the release of a considerable amount of energy (approximately 4.1 kcal in the oxidation of 1 g of carbohydrate) which is used for different physiological processes.

Some carbohydrates are soluble, and some insoluble. Sugars belong to the first, and starch to the second group.

Sugars are rapidly utilized by the organism. The sugars most widely found in foods are: glucose, saccharose, lactose, and fructose. Pectin substances are close to carbohydrates in terms of their chemical composition and properties. Vegetables have a high content of pectin substances. The latter participate in the metabolism of food and they stimulate the work of the intestine.

The daily diet depends on the character and exertion of the physical efforts of man. It is believed that brainwork and automatic physical labor require a daily diet containing 350-400 g of carbohydrates. /15

For the normal development and the vital activity of organisms, food must contain vitamins, in addition to proteins, fats, carbohydrates, mineral salts, and water.

Vitamins are varied depending on their chemical nature, and are needed by the organism for the formation of enzymes and hormones for the stimulation of various biochemical processes, etc.

The absence or deficiency of vitamins in food produces various kinds of disorders and diseases (scurvy, beriberi, pellagra, and others).

On the average, for an adult person the daily quota of vitamins to be introduced into the organism is: /16

Vitamin A	1.5 mg
Vitamin B_1	2.0 mg
Vitamin B_2	2.5 mg
Vitamin B_6	2.0 mg
Vitamin PP	15.0 mg
Vitamin C	70.0 mg

The norms for the remaining vitamins have as yet not been established. These vitamins are present in normal daily diets and, ordinarily, with normal nutrition no avitaminosis is observed.

In addition to vitamins, it is necessary that an adequate amount of mineral substances should be introduced with food.

Ordinarily, all mineral salts found in the organism are divided into macroelements and microelements. The macroelements include those salts whose content in the tissues is expressed in percents or fractions of a percent (calcium, phosphorus, potassium, sodium, magnesium, chlorine, sulfur). The microelements include salts found in tissues in amounts less than a hundredth of a percent. The most important are: copper, zinc, cobalt, manganese, iodine, fluorine, and others. Iron occupies an intermediate position.

We shall not dwell on the physiological role of each element, but shall rather confine ourselves to data on the daily requirements of man for the basic elements of mineral nutrition (see Table).

In addition to food, a man must consume regularly a definite amount of water. Water is the basic medium in which numerous biochemical reactions occur; 67-68% of the total weight of man is water.

Daily human requirements for mineral salts (in mg)

Macroelements		Microelements	
Calcium	800-1000	Cobalt	10
Phosphorus	1500-1600	Iodine	1-1.5
Magnesium	500-600	Fluorine	1
Potassium	2000-3000	Copper	2
Sodium	4000-6000	Zinc	5-10
Chlorine	4000-6000	Iron	15
Sulfur	800-1000		

The human organism controls the degree of hydration of individual organs and tissues, and closely regulates the input and ouput of water in them. Constant water content of all parts of the organism is a necessary condition for normal vital activity. A disturbance of the normal water content leads to serious disorders in the organism.

Water metabolism proceeds in the human organism quite intensively. It has been established that, under a comparatively small physical load and at a normal ambient temperature, a man expels daily about 2.5 l of water. This amount includes water secreted with urine, with excrement, as sweat, and also with exhaled air.

The human organism releases more water than it takes in with food and fluids because, as a result of the biological oxidation of food, it forms additionally about 300 ml of water daily. It is known that the oxidation of 100 g of fats releases 107 ml of water, 100 g of carbohydrates yield 55 ml, and 100 g of proteins yield 41 ml of water. In order to maintain the vital activity of the human organism, man must take in daily the same amount of water as he expels.

Daily water balance of man of 70 kg weight (in ml)

Input

Intake of water with food	700
Intake of water with liquids	1500
Water from oxidation processes (metabolic water)	300
Total	2500

Output

Excretion of water with sweat	500
Excretion of water by the lungs	400
Excretion of water with urine	1500
Excretion of water with feces	100
Total	2500

As pointed out earlier, the energy source for all human processes are substances absorbed as food and oxidized in the organism most frequently to carbon dioxide and water. A continuous intake of oxygen is needed for continuous oxidation processes. Nature wisely took care of this and, during a prolonged evolutionary process, created a complete and finely regulated respiratory apparatus.

An adult healthy man in a reclining position performs 14-16 breaths per minute; in a sitting position, the number of breaths increases to 20; in a standing position — to 22 breaths per minute. With physical exertion, the frequency of respiration increases. The number of breaths per minute by our cosmonauts during space flights was close to 20. /17

About 500 ml of air is ordinarily inhaled. However, the volume of the lungs is considerably greater. After smooth inhalation, it is possible to introduce additionally into the lungs another 1500-2000 ml of air, and after ordinary exhalation it is possible to exhale additionally 1000-1500 ml of air.

Under resting conditions, a healthy person inhales approximately 10,000 ml of air per minute. This is called lung ventilation. This amount of air contains 2000 ml of oxygen. However, only 15-20% of oxygen introduced into the lungs during inhalation is absorbed by the human organism. The amount of absorbed oxygen, corresponding to lung ventilation, is called the coefficient of oxygen utilization. In a resting state, this coefficient is usually equal to 30-40 ml per liter of air used in respiration. Heavy physical work gives a higher coefficient.

Simultaneously with ensuring the organism with oxygen, respiration also removes from the organism carbon dioxide formed as a result of food oxidation.

In order to remove 1 ml of carbon dioxide from the human organism, 30-45 ml of air must pass through its lungs. This value is termed ventilation capacity.

The characteristics of the respiratory apparatus make it possible to calculate the daily requirement of man for air, oxygen, and to determine the respiration coefficient (ratio of exhaled volume of carbon dioxide to the volume of absorbed oxygen).

Thus, it is not difficult to calculate that the total amount of oxygen inhaled daily by man is 14-15 thousand liters. This amount of air contains about 3000 *l* of oxygen, of which approximately 600 *l* of oxygen are absorbed by the organism. Simultaneously, the respiration coefficient is on the average equal to 0.83.

It must be noted that the coefficient of respiration (CR) under the influence of different foods may vary from 1 to 0.71. In feeding primarily with carbohydrates, the CR is equal to 1. For protein it is equal to 0.81, and for fats — 0.71.

It is known that not all the food absorbed by man is assimilated by the organism. All that is unnecessary to man is removed from the organism as solid and liquid secretions. The amount and composition of solid and liquid excretions both depend on the character of the food. In mixed (meat and vegetable food) diets, a healthy person excretes daily 120-180 g of feces (150 g average). /18

Chemical composition of feces from a healthy person (daily)

Water	100-120 g
Nitrogen	0.25-2.0 g
Phosphorus	200-700 mg
Potassium	7-12 mg
Calcium	400-900 mg
Magnesium	5-18 meq
Sodium	1-5 meq.
Sulfur	71-150 mg
Fats	2.5-10 mg

The amount of different organic substances is:	1-2 g

Among various organic substances with components totaling about 1-2 g, precise modern methods of chemical analysis have determined 196 various compounds.

The liquid excretions daily by a healthy person is 1500-2000 ml (1800 ml average). Ordinarily, 90-95% of the total amount of urine is water, and 5-10% is dry residue. The composition of urine is extremely complex. Over 30 inorganic substances, 16 vitamins, about 10 hormones, and a large amount of various organic substances have been determined in it. The total number of various substances successfully determined in urine has reached 183.

Content of basic elements found in human urine
(calculation based on the daily amount eliminated by one person)

Nitrogen, total	15 g	Calcium (CaO)	250 mg
Nitrites	0.5 g	Magnesium	250 mg
Potassium	2.8 g	Sodium	4.5 g
Phosphorus	0.9 g	Sulfur	2.6 g
Iron	0.08 mg	Chlorides	12.5 g

Aside from solid (feces) and liquid (urine) excretions, the human organism excretes sweat and fat. Each square millimeter of the skin surface contains about 120 sweat glands. Sweating is regulated mainly by the nervous system and depends on both external factors (temperature of medium, character of nutrition, hydration of organism, and others) and internal factors (state of central nervous system and others). On the average, a person secretes daily 500 ml of sweat.

The chemical composition of sweat is rather complex. Human skin excretions contain 271 components. This includes 98% water, up to 0.8% sodium /19 chloride, 0.05% urea, 0.01% ammonia, negligible amounts of lactic, citric, and ascorbic acids, traces of potassium, calcium, magnesium, phosphorus, sulfur, protein compounds, and other substances.

Another substance lost by man is saliva. Three pairs of salivary glands and small glands located in the mucous membrane of the mouth cavity produce saliva. An adult person secretes daily up to 1.5 l of saliva. Saliva, wetting the food, facilitates its swallowing and digestion. The chemical composition of saliva and its amount may vary depending on the food composition and on the nervous state of the organism. Saliva contains 149 various substances.

In all, a man excretes over 400 various organic and inorganic substances. Most of the substances are present in human excretions in negligible amounts hardly detected by the most precise methods of modern chemical analysis. Under ordinary living conditions on Earth, most of the substances do not have to be considered, because with steady ventilation of living areas these substances are scattered in an infinitely large volume of atmospheric air. However, in the creation of artificially closed systems in a limited volume with comparatively small amounts of air, human excretions may accumulate in noticeable amounts and become toxic. Therefore, in the creation of closed life-support systems, it is necessary to account for all human excretions regardless of their negligible amounts and take measures for detoxification of the atmosphere of inhabited compartments in closed systems.

Thus, a person for his normal life and work needs a daily food ration containing approximately 3000 kcal, including 80-100 g of proteins, 80-100 g of fats, and 350-400 g of carbohydrates. A diet must contain at least the necessary amount of all indispensable amino acids, vitamins, and mineral salts. Daily, a man must take in about 2500 ml of water (including water contained in solid food) and approximately 600-650 l of oxygen.

In closed areas, the inhabited premises should be free from the products of the vital activity of man: carbon dioxide, solid and liquid excretions, and also other substances.

For graphic illustration, the "input" and "output" of various substances used by man are presented in a diagram (Figure 2)

To these human requirements (to the "input" and "output" of various substances) should be added the remaining links of an artificially created microworld, or, as they say, a system containing a closed cycle of substances.

The artificially created cycle of substances on board spacecraft or on a planetary station can be accomplished by imitating, copying, or reproducing /20 the cycle occurring in nature.

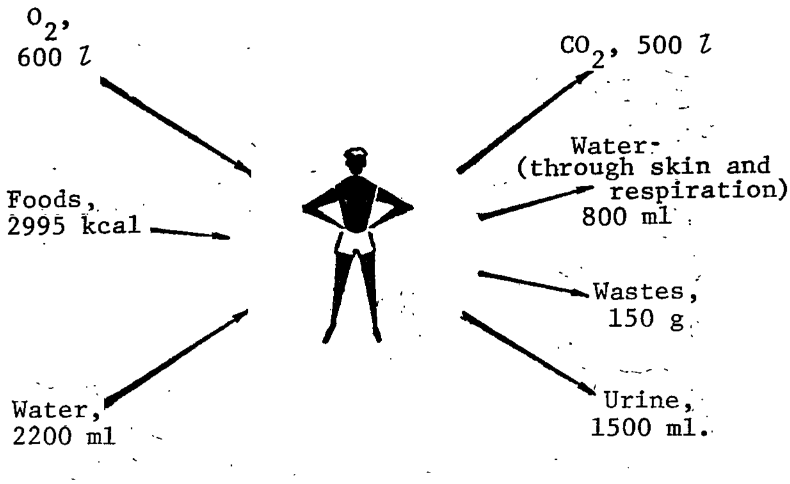

Figure 2. Average "input" and "output" of substances from a man daily.

How is the Cycle of Substances Accomplished in Nature?

The main links in the cycle of matter in nature are the living organisms, due to their ability to exchange substances and energy with the surrounding medium.

A large variety of organic forms appeared on Earth during the evolutionary development. This diversity was necessary for the coexistence of organisms which differed with respect to their participation in the cycle of matter in the biospheres. Each living creature draws substances and energy from the external medium and returns to the medium other substances which are unsuitable for supporting the life of other individuals of the same species. Part of the energy obtained from outside is accumulated in the organism, and is consumed by it for supporting life processes. The remaining energy is converted to heat, and is dissipated.

Life on Earth could and can develop only under conditions of a continuous cycle of matter, and this is possible only under conditions where organisms exist with different requirements and where the products of the vital activity of one group of organisms are utilized to support the vital activity of /21
another group.

As a result of the long process of evolution on Earth, two large groups of organisms differing in their method of nutrition and their method of obtaining energy were formed.

The first group includes photosynthesizing organisms — green plants and also purpura bacteria. This group of organisms is termed autotrophs ("self-feeding"): they live, feed themselves, grow, and multiply, using inorganic salts, carbon dioxide, and water from the surrounding medium. The radiant energy of the Sun is an energy source for the biosynthesis of these organisms. The autotrophic organisms also include some bacteria which receive energy in the oxidation of definite mineral compounds by enzymatic systems. These organisms are called chemosynthetics.

The second group (heterotrophs) includes organisms incapable of creating organic substances from simple compounds. They are forced to feed themselves with autotrophic organisms or dead remnants of other organisms, and to ensure their requirements they use organic substances and energy accumulated by them.

Human beings, all animals, fungi, and most bacteria belong to the heterotrophs.

Heterotrophic organisms are divided into three subgroups on the basis of their method of nutrition:

1. Organisms which swallow and assimilate food with the help of the digestive system.

2. Organisms which absorb the necessary substances directly through their cells (saprophytes). These include: yeasts, mold fungi, and most of the bacteria. Saprophytes can grow and develop only in the presence of dead decomposed remnants of plants or animal products.

3. Finally, the third type of heterotrophic nutrition includes parasitism. Parasites live on the body (or inside) of the host organism and feed themselves at his expense. They either swallow and digest definite substances of the host organism or obtain it directly through the cell walls.

Thus, for a complete cycle of matter on Earth, it is necessary to have two groups of organisms: autotrophs — producers of organic substances and accumulators of solar energy, transformed into the energy of chemical bonds, and heterotrophs — consumers of organic substances produced by the autotrophs. Saprophites, microorganisms destroying the organic substance of dead bodies of plants and animals, and converting them into a form accessible to autotrophic organisms, are also necessary.

The combined existence of these groups of organisms constitutes a complete association, capable of cycling matter and energy. This kind of association of various living organisms, considered together with the nonliving elements of the environment, is known as an ecosystem. Ecosystems can be of varying complexity and size. Large forests, lakes, swamps, etc., are examples of ecosystems. /22

A pond is often the classic example of an ecosystem. The nonliving elements of nature in this case are the water, mineral salts which are always present in water, as well as the gases dissolved in the water — oxygen and carbon dioxide. To the nonliving elements, we must add the shore and the bottom of the basin. Living elements of nature in such an ecosystem are the photosynthesizing plants which create organic matter from elements and store energy.

Two kinds of photosynthesizing organisms are most frequently found in the basin. These are large water plants which are distributed primarily along the shore, and microscopic, often unicellular, algae found at all water depths reached by the Sun. The production of organic material by microscopic algae usually somewhat exceeds that of the large water plants.

The consumers organisms in such an ecosystem are various insects and their larvae, mollusks and fish.

Destructive organisms are the multitudinous bacteria and fungi which feed on dead bodies of both plants and various heterotrophic organisms and convert them into inorganic matter, again suitable for use by plant-producers.

Among heterotrophic organisms there are primary, secondary, and tertiary consumers. The first of these eat plant food (leaves, stalks, fruit, seeds, roots or sap of growing plants) and are, therefore, called herbivores (phytophagous). The secondary consumers are heterotrophic organisms whose food is the herbivorous animals. This group of organisms is called carnivorous, predators or zoophagous.

Among the many representatives of the various groups of heterotrophic organisms, there are purely phytophagous or zoophagous types which feed exclusively on plant or animal food. Just as widely distributed is mixed feeding when one kind feeds on both plant and animal food. Man is a member of this group.

The tertiary consumers, the above-mentioned saprophytes, feed on the organic matter or dead plants and animals. /23

In this way a food chain is compiled. The plant, consuming inorganic matter and radiant energy from the Sun, creates organic matter and stores energy. The organic matter of the plants and the energy included in them serve as food for phytophagous organisms. These are in turn eaten by zoophagous organisms, which use the organic matter of the phytophagous and the energy they contain to maintain their life activity. Finally, the dead bodies of all kinds of life are the food and energy source for the sapophytes. In the vital processes, these mineralize organic materials and again prepare food elements for plants. However, phytophagous and zoophagous organisms also partially mineralize organic materials. Man, in particular, as a heterotrophic organism returns approximately 80-85% of his food ration to the cycle. Thus, the cycle is completed.

We shall now observe the energy cycle.

As already noted, the primary source of energy for all organisms is sunshine. However, living organisms use only a small part of the radiant energy of the Sun which reaches the surface of the Earth. Numerous studies have established that only 1-3% of all radiant energy from the Sun is converted into the potential energy of growing food plants. All remaining solar energy is converted into heat, and is dispersed. In addition, the large part of potential energy contained in the vegetation eaten by herbivorous animals is also converted into heat and dispersed. When the herbivorous animal falls prey to the carnivore, only a small portion of the energy in the victim's body is assimilated for use by the consumer. The basic part of the energy is also converted into heat and, being dispersed, loses its value.

Thus, the transfer of energy along the food chain from one group of organisms to another is accompanied by significant losses. The first link, the photosynthesizing plants, assimilate only 1-3% of the available sunlight. Succeeding links of the chain convert energy with somewhat more effectiveness — from 5-20%. It is perfectly natural, with such great energy losses in the transfer from one link in the chain to the next, that each succeeding link has fewer representatives and a smaller allover quantity of the biomass.

All the biological links in an ecosystem can be represented as a pyramid with a wide base, each succeeding link of the pyramid is much smaller. Their size is 5 to 20% smaller than the base (Figure 3).

The well-known American ecologist, G. Odum, has calculated that it takes 8000 kg of alfalfa, produced from 20 million plants, to feed calves with an average weight of about 1000 kg (4.5 head). The meat from these calves would provide enough nourishment to grow one boy to an age of 12 years, weighing 47 kg. Naturally, the calves would not eat only alfalfa, and the boy would not eat only the meat from these calves. However, these calculations show the real quantitative relation of various levels of the food chain in ecosystems. Evidently, in view of such great energy losses in the transfer from one link to the next, the maximum length of food chains in ecosystems is 4-5 links. /24

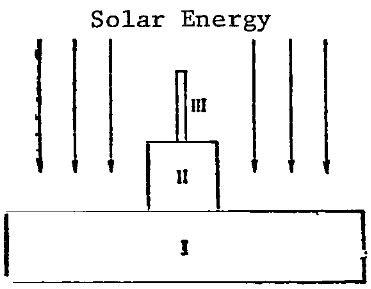

Figure 3. Ecosystem "pyramid": I - autotrophic organisms, II - heterotrophic phytophagous organisms, III - heterotrophic zoophagous organisms.

Let us turn to considering the cycle of matter in a particular ecosystem (in our example — a pond).

Inorganic materials are consumed by autotrophic organisms, which convert them into organic matter to serve as food for heterotrophic types. Then, with the help of the saprophyte population of a given ecosystem, organic matter is again decomposed into the original components of regular autotrophic nourishment.

However, there is no certainty that the atoms of various compounds which at one time were used in the biological cycle of matter will be included a second time. It is rather to be expected that material mineralized by destructive organisms will precipitate to the bottom of the basin, to be released at some future time from the cycle of matter.

In our pond, new portions of matter also constantly appeared with spring water, with rain, as a result of wind, etc. Thus, the producer-organisms have new portions of nutritional matter "at hand."

The same can be said for carbon dioxide, assimilated by photosynthesizing organisms from the atmosphere. There is a constant transfer of huge air masses, and the possibility of a second or more frequent use of the same /25
molecules of carbon dioxide by living organisms is very small.

Solar radiation is constantly flowing into our ecosystem, but only a small part of it is used in the synthetic activity of autotrophic organisms. The remaining energy is converted into heat and dispersed. A significant quantity of energy is also dispersed in transfer to other trophic levels of the ecosystem.

Thus, in considering our ecosystem, we see that a continuous stream of energy and matter is passing through it.

From the point of view of thermodynamics — the division of physics that studies the exchange of heat and matter through the boundaries of systems — our ecosystem is an open system, i.e., one in which energy and matter are exchanged with an external medium.

If we consider the entire Earth as a single ecosystem, then we discover that the mass of matter on the Earth is practically constant. The quantity of matter on the Earth does not increase or decrease, but is only transformed, changing from one state to another.

Systems which exchange energy, but not matter, with the environment are called closed systems.

However, it is theoretically possible to imagine a system which exchanges neither energy nor mass with the external environment.

We are chiefly interested in closed systems, as in the creation of a closed cycle of matter, it is assumed that the quantity of matter placed in a sealed space would be constant. Only energy is derived externally.

Only by comprehending the character of the biological cycle of matter and energy in nature and understanding the objective laws governing the development of natural ecosystems, will it be possible to learn to imitate nature, to copy it, not to mention subjugating it.

It is appropriate to remember how I. V. Michurin has emphasized so many times that man can act in nature only as "nature itself operates." He scoffed at those who, having hardly penetrated the secrets of nature, shout about conquering it, "exactly like Krylov's fly on the horns of the ox, who imagined he was pulling the plow." Illustrating this same idea by an everyday example, Michurin wrote: "If I found a crack in my neighbor's fence and through it I saw how he does some kind of work, it would be silly for me to shout that I had conquered my neighbor and not humbly to realize that because of the example I had seen I could now, by using the methods of my neighbor, do the job better than I had done it before."

We have already mentioned that it is hardly possible that the very same atom of a particular substance participating in the biological cycle of matter would be used by the same plants a second time. /26

At the same time, calculations indicate that the overall weight of living beings on our planet hardly constitutes 0.01% of the weight of the planet. But, for the many millions of years of the existence of life on Earth, the total weight of all life for all generations by far exceeds the weight of the Earth.

How could this be produced?

Along with the biological (sometimes called the small) cycle of matter in nature, there is a geological (or large) cycle of matter.

It is known that a large part of one of the most important elements on Earth for the vital processes of organisms, carbon, is found in rock, for example, in the form of carbonates, limestone and marble. Rocks, during many thousands of years under the influence of external factors — wind, rain and sun, as well as certain chemical elements — disintegrate and free the carbon contained in them, which is then included in the biological cycle. At the same time, if dead plants are under water without access to air, where they often experience great external pressure, they will not decompose. A number of changes occur in them, and the former plants can be turned into peat, brown or bituminous coal. In this case, the carbon in them is excluded from the biological cycle of matter.

Only an event on a geological scale, for example, volcanic activity or the activity of man (mining and burning of coal, peat, etc.) restores this carbon to the sphere of activity of the biological cycle.

In a similar manner, other elements (phosphorus, potassium, calcium, magnesium, etc.) are withdrawn and accumulated in forms inaccessible to living organisms and also returned to the biological cycle as a result of geological processes and phenomena.

All that has been said in this chapter refers to natural processes and phenomena. It is our object, having considered the cycle of matter in nature, to ascertain the possibility of creating an artificial system patterned after and similar to the natural one. In other words, to build a model of the natural cycle in an artificial closed system.

Modeling Nature

/27

Man is always learning from nature, imitating and creating something similar to what he sees in nature. Ancient man first of all threw seed that he had collected from plants onto loosened soil and waited for the harvest; he imitated nature.

One of the oldest and simplest examples of pure simulation is the construction of models of space.

Since ancient times man has drawn plans, made maps, depicted the surface of the planet on a globe. Now modeling processes and phenomena is a very widespread technique, used in many sciences. Modern modeling is firmly supported in logic and mathematics. Cybernetics successfully models various control systems. The chief goal of the young science of bionomics is to study creative nature, and imitating nature to create perfect mechanisms to be used by man.

The progress of science and industry makes it possible to create more and more complex, perfect, and accurate models of very intimate processes and phenomena. Thus, medicine has at its disposal "artificial lungs", the poultry-raising industry has long used an incubator to successfully simulate a brood hen.

In ordinary life, at the present time, there is no clear-cut use of the term "model". The new construction of an automobile, or some kind of machine, is called a model. This same term often designates a certain ideal standard from which other examples of the same type are copied. Often the term model is used for a material reproduction of an object or process irrespective of purpose — for example, construction on a small scale of projected hydro-electric stations, reproduction under laboratory conditions of a technological process of chemical production, etc.

Originally, man, modeling natural processes or phenomena, relied mainly on his own intuition. Relying on intuition, not being guided by strict logic and accurate mathematical calculation is a risky business. The history of civilization knows the tragic results when attempts to imitate nature, to model it without a solid basis in logic and mathematics, have led to catastrophe. Daredevils with the "wings of birds" have been killed attempting to imitate (model) the flight of birds. Steam vehicles have blown up, etc.

In the middle of the last century, Bertran devised the principles of a mathematical theory of similarity. Modern science has brought modeling into the field of accurate analysis and calculation. Modeling has been widely /28
developed and is used for various purposes. Among the official purposes, three main ones may be noted:

1) the created model serves research purposes. Laboratory development of technological processes is a good example of this case;

2) modeling for the purposes of education. The many plans, tables, maps, etc., without which it is impossible to imagine the modern pedagogical

process in school, illustrates very well the role of this kind of model;

3) reproduction of an object for applied and practical purposes. Essentially, this is direct imitation of nature, however, with possible simplifications.

Most directly of interest to us is the third purpose of modeling — reproduction of an object (cycle of matter), occurring in nature, with possible simplifications.

Strictly speaking, the concept of "reproduction" of an object is certainly wider than "modeling". Artificial reproduction is the creation of material analogs of an object which occurs in nature. This is what we need.

The creation of a material model of an object or process is often preceded by the construction of an ideal (mathematical or calculated) model of that object.

The ordinary plan of action in solving a scientific or practical problem is as follows: statement of the problem, which can and should be solved with the help of modeling. Then observations and experiments follow, in the course of which active interference of the experimentor is necessary during the creation of the necessary model.

It must be noted that a need for modeling and the possibility of constructing a model only appear when the studied system is partially understood. Of course, the creation of any model must be preceded by the development of a working hypothesis.

In our case, it is a matter of reproducing on a microscale processes of the matter cycle which occur naturally in nature. This process is well understood, and we must set it up under artificial conditions. We reconstruct it with possible simplifications because, as was mentioned, the matter cycle in nature has an incommensurably large reserve of matter.

In an artificial ecological system, intended for spacecraft, lunar or planetary stations, the quantity of matter included in the cycle must be at a minimum, only just exceeding the critical level to realize the cycle.

The creators of an artificial ecological system are interested in the minimum amount of matter and most rapid circulation. On the other hand, complete cycling of all matter without exception is hardly possible in an artificial system with minimum amounts of matter. It is probable that some matter will drop out of the cycle and be deposited at certain stages. This demands compensation for them by supplementing from the reserve, or by recycling. /29

There has been suggested, and is being discussed, in the scientific literature a number of schemes for an artificial matter cycle in closed space with a constant amount of matter, and open in terms of energy.

The most tempting would be, of course, to create a two-component system: man — plants, which has already been suggested by K. E. Tsiolkovskiy. In the beginning of the development of this problem, significant efforts were made to realize this (two-component) system. This was synchronized with the development of research on the economic use of unicellular algae (as food, fodder and industrial raw material). In the huge mass of various microscopic algae, attention was first of all given to chlorella.

Chlorella (as well as several other algae) has a number of biological traits which make its use very enticing in closed ecological systems. Chlorella has no rest period in its development. Its cells are continuously able to feed, grow and reproduce, forming the biomass, discharging oxygen and absorbing carbon dioxide. Chlorella reproduces itself by forming autospores in its cell, and the subsequent division of this cell into 4-16 daughter cells, each of which is capable of independent life and further reproduction.

Success in the selection of chlorella in recent years has made it possible to create highly productive forms which, under favorable conditions, pass through the complete development cycle in 6-8 hours. The best modern strains of chlorella are able to accumulate a large biomass and to produce up to 50 or more liters of O_2 a day from 1 liter of suspension. The biomass of chlorella (cells separated from the nutrient solution) contains a high percentage of protein, fats, and other nutrient materials. Therefore, in solving the problem of regenerating water and air, as well as feeding the cosmonauts, great hopes were pinned on this tiny alga. It was and is the subject of much research. In particular, these studies were conducted by A. A. Nichipporovich.

At the present time, chlorella is a good regenerator of the atmosphere /30
and water. A number of successful prolonged tests are known on the use of chlorella as a regenerator of air for man in pressurized cabins. But it is still too soon to talk about chlorella as food. The tough outer layer of the chlorella cell creates definite difficulties in processing its biomass. We have already mentioned that, in forming the food ration for cosmonauts, we must not ignore man's individual traits, habits, and inclinations. A successful diet has not yet been created from the chlorella biomass which will satisfy man's taste. Therefore, attention of researchers has turned to higher plants.

However, attempts to design a two-component system using higher plants as autotrophic organisms have met with great difficulties, and it is easy to see the unreality of establishing a cycle in such a system.

A two-component system cannot completely provide the food needs of man. For fully-adequate nutrition, a certain number of animal proteins are necessary, as not all noninterchangeable amino acids are produced by plant organisms.

In a two-component system, approximately half of the biomass formed by higher plants (tops, roots) cannot be used by man. It can be used as food for other heterotrophic organisms.

Human experiments can use higher plants in natural, unprocessed form only to a limited extent. Human wastes must be processed (mineralization of organic matter, decomposition of components which are toxic for plants). Only after this can they be used as fertilizer.

However, it is extremely difficult to balance the "entrance" and "exit" of all links of an artificial small system for all the matter. In connecting individual links of the system, some matter will inevitably be excluded from the cycle; it will accumulate at individual stages of the complex cycle process. This demands careful control of the movement of matter and correction by replacing the precipitated matter in the cycle from the reserves or by appropriate processing of it into combinations which could again be included in the cycle.

This all greatly complicates plans for a matter cycle in artificial closed ecological systems.

We shall cite one of the possible plans for a complete cycle of matter in a closed ecological system (Figure 4).

An artificial ecological system, based on the biological cycle of matter, /31
is created to provide normal living conditions for man in a long space flight to the Moon or the planets. Consequently, man, with his needs and norms, is the central link in the system, and his vital processes contribute to the steady functioning of the whole cycle.

Man, consuming the oxygen produced by the plants, is, in turn, a supplier of carbon dioxide for the plants. He is a consumer of products created by the autotrophic and heterotrophic organisms.

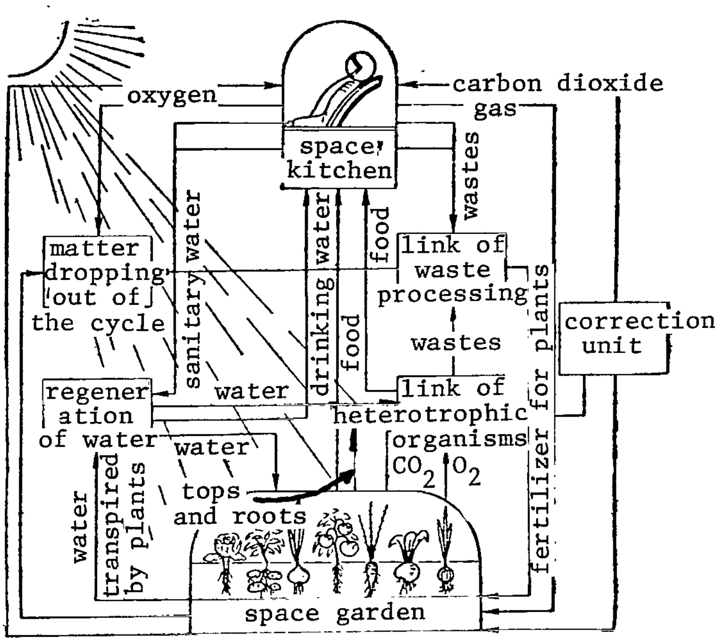

Figure 4. One of the possible plans for a cycle of matter in an artificial closed system.

If, for any reason, sickness for example, the human organism ceases to function normally and decreases his activity, this influences his appetite, on the one hand, and his excretions, on the other. If man does not produce a certain amount of carbon dioxide and wastes, this will entail a changed work regime for other links in the system: the quantity and composition of fertilizer for the plants is changed, the intensity of photosynthesis, the amount of oxygen received from the plants, water, food created by the plants, etc. In short, an unbalanced system will occur. This is one feature of the functioning of an artificial ecosystem created to satisfy the needs of man in space.

A cycle of matter in any system needs energy. The single "entry" of energy into the system we have been considering and its primary accumulator is photoautotrophic plant organisms. They convert radiant energy from the Sun into potential energy of chemical bonds. This energy, moving through the entire system of the cycle, provides the energy needs of all the links, including man. /32

In our opinion, the link of photoautotrophic plants in the system must be considered as the chief link in the whole cycle. In the following account, we shall limit ourselves to considering just this link.

The Link of Higher Autotrophic Plants

Botanists number about 250,000 different kinds of higher flowering plants on Earth. But only 2558 kinds are used by man for food.

The kinds of plants constantly being consumed include: vegetables — 546; root-crops — 261; legumes — 83; cereals — 74, etc. In the Soviet Union, about 450 kinds of plants are cultivated.

The choice is large. What kinds should be used to create a link of higher autotrophic organisms for a closed ecological system? What should guide the choice of plants for this purpose?

The principles of choice of agricultural plants for inclusion in the chain of closed ecological systems is being widely discussed in scientific institutions and in the press. We suggest that, in solving the problem of choosing plants, it would be logical to consider the following facts.

Agricultural plants, included in the link of a closed ecological system, must first of all be high-yielding and satisfy man's nutritional needs. It is necessary to consider not only the total yield, but also the biochemical composition, the content of proteins, amino acids, fats, carbohydrates, vitamins and mineral salts. All the included agricultural plants should be natural for man and exist in the same environment. Identical conditions for /33 raising different (all) plants included in the higher-plant link will simplify the technical problem of creating cultivation rooms in spacecraft or lunar and planetary stations. In that case, the cultivation rooms would not have to be divided into several sections to give each part its own complex of conditions (temperature, light, moisture, etc.).

It is also desirable that the demands of plants and man on environmental conditions be similar. This would eliminate the necessity for creating and maintaining different climatic conditions in the living quarters and cultivation rooms of space vehicles or planetary stations.

The compatability of all the chosen plants with each other and with man, for whose well-being the whole system is being created, is very important. Quite a few plants, as a result of their vital processes, exude through their roots or leaves various substances which can definitely affect their neighbors (positively or negatively): some excretions, especially gases, could be toxic for man. Finally, one cannot help taking into account the complexity of technology in preparing food for man from harvesting cultivated plants.

In fact, let us imagine that wheat or some other kind of cereal grain is included in the number of plants. The ripe ears need to be threshed, the grain dried, ground, then a dough prepared and baked. In all — five technological operations which need specific areas (for harvesting, grinding, etc.) and space. Moreover, all these operations take quite a lot of time.

Vegetables, including tuber- and root-bearing plants, can be used for food immediately after harvesting. Evidently preference must be given to these kinds of plants.

In works where plants rich in carbohydrates are discussed, those included in the link include potatoes, sweet potatoes, sugar and red beets, rice and wheat, as well as a number of starchy plants from tropical regions of the Earth: yams, colocasia (taro), manioc, topinambur (ground pear), etc. Protein plants include bean, soy-bean, other beans, peanut. Vitamin-rich plants include onion, various cabbages, especially Chinese, kohlrabi, radish, lettuce, spinach, parsley, fennel, tomato, etc. Finally, plants which contain various tonic substances are not forgotten: maté-tea, savory, balm mint, and a number of others.

These plants far from exhaust all types which could be considered for the "kitchen garden" of future cosmonauts.

It is hardly possible that one kind of plant can be expected to provide men in space with food, water, and air. Obviously this could be taken care of by growing a whole collection of plants in the space plantation. In this case, it would be easy to provide a more complete and varied diet. /34

In foreign publications, a number of diets for man are being discussed which are based on growing in the craft peanuts, lima beans, topinambur, leaf cabbage, potatoes, maize, lettuce, tomatoes, as well as a certain quantity of yeast. Diets made up of these crops satisfactorily supply the nutritional needs of man according to basic characteristics: total calories, protein content, carbohydrates, fats, mineral salts, vitamins and amino acids except methionine.

We have already mentioned that the principles governing the selection of plants for the diet must include man's habits with regard to different kinds of food. Peanuts, topinambur and lima beans are little known to Russians; it is advisable to compose a diet for Soviet cosmonauts from plants cultivated in the USSR. Calculations indicate the possibility of doing this. However, it must be noted that it is impossible to make a collection of plants which could completely meet man's needs for all the necessary nutritional elements, since plant proteins, as indicated above, are not fully adequate for man. They lack sulfur-containing amino acids, and the human organism cannot synthesize them. They are obtained in prepared form in food from animals.

This problem can be solved in two ways: either animal-produced proteins are taken on board the spacecraft from Earth, or in the closed matter cycle system a link of heterotrophic organisms is created which is capable of synthesizing the animal proteins that man needs.

It would be most efficient to choose those heterotrophic organisms which would use the tops, roots, and other parts of the cultivated plants considered inedible by man. Evidently, several heterotrophic organisms capable of producing complete proteins can be nourished by algae (chlorella). However, the problem of constructing a link of heterotrophic organisms has drawn us aside from our basic purpose.

From the above, a conclusion can be drawn which is exceedingly important for the general formulation and solution of the problem of creating a link of higher plants in the system.

At first, a closed matter-cycle system would be incomplete. The cycle produces part of the matter; the rest is added from reserves. In connection with this, studies are being made of variations of the link of higher plants, in which the minimum amount of growth necessary to create vitamins which cannot be stored for a long time is produced on board the spacecraft in a /35 limited area. Even a small addition of fresh vegetables to the concentrated food from the reserve decorates the diet and increases its taste quality. Calculations, as well as tests, indicate that growing vitamin-rich vegetables in an area 3-4 m^2 can provide all the needs for one man.

Concerning the regeneration of air and water, 3-4 m^2 of crops will give a limited amount of oxygen and transpired moisture. In this case, it is necessary to replenish oxygen from other sources (from reserves or from electrolytic decomposition of water).

Various other variations of a link of higher plants are possible with larger areas for growing plants, and consequently, with greater food production for man, with a greater degree of atmosphere and water regeneration up to completely supplying the needs of man for plant food and creating the necessary nutrition for heterotrophic organisms.

As an example, we shall present one of the many collections of plants which could work satisfactorily in a link of higher plants in a closed matter cycle system and would provide a large part of man's needs: potatoes, white cabbage, leaf cabbage (Chinese), carrots, beets, radishes, and tomatoes.

We shall attempt to formulate a link with this collection of plants /36
and to determine if it can provide man's needs for food, water, and oxygen. In other words, we shall attempt to create a mathematical model of this link of the system. In calculating the size of the link of higher plants, we first consider man's daily food needs. Based on calculations of nutrition specialists, the following norms of man's daily needs can be assumed in the cultures we chose (see p. 42).

This diet provides man with 30% of the energy, 25-30% protein, 60% carbohydrates, complete high-ash elements, and more than enough vitamins. The diet contains a sufficient amount of amino acids, except the sulfur-containing ones (methionine).

Relying on existing published data on harvests actually produced under artificial conditions and critically evaluating them, the following harvests of the selected crops can be assumed for a certain growing period.

The work of the entire link can be calculated according to the assumed daily human diet as well as the chemical composition of the food, the length of the growing period, and productivity. These data make it possible to determine the minerals necessary to feed the plants, the necessary correction for the nutrient solution which is constantly being depleted as a result of the plants absorbing the materials, and also to determine the amount of transpired water, the production of oxygen, and the plants' need for carbon dioxide.

The result of these calculations is given in Figure 5, where the daily balance of matter "entering" and "leaving" the link of higher plants is shown.

This diagram can essentially be called a model of the link. /37

Conceiving the model and designing it in all its details is still only half the job. The second half and the most difficult is to create this model in nature. A great many problems appear which never were encountered

	Daily ration in uncooked weight (g)	Calories (kcal)	Content			
			Protein (g)	Fat (g)	Carbohydrates (g)	Ash (g)
Potatoes	900	846	18	—	189	9,0
Cabbage, white	100	30	2	—	5,4	1,2
Cabbage, Chinese	100	15	1,5	—	2,2	0,8
Carrots	50	19	0,7	—	4,0	0,4
Radishes	50	11	0,6	—	2,0	0,35
Beets	50	25	0,7	—	5,4	0,5
Tomatoes	200	44	1,2	—	8,4	0,8
	1450	990	24,7	—	216,4	13,05

	Growing period (days)	Harvest of edible parts (kg/m^2)	Necessary area (m^2)	Harvest of inedible mass (kg/m^2)
Potatoes	90	8,5	11,2	8,5
Cabbage, white	90	7,0	1,5	4,6
Cabbage, Chinese	40	10,0	0,4	1,3
Carrots	90	8,0	0,6	4,0
Radishes	25	5,0	0,3	5,0
Beets	90	7,5	0,7	7,5
Tomatoes	90	12,5	1,6	12,5
		58,5	16,3	43,4

Translator's Note: Commas represent decimal points.

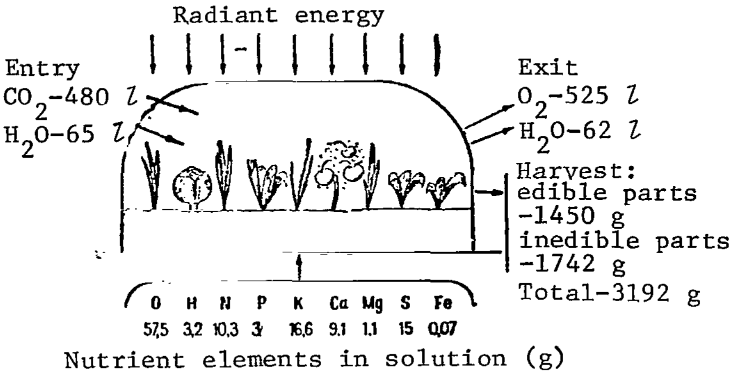

Figure 5. Daily balance of matter in the link of higher plants (per 16 m^2 of planting).

before in plant culture. For example, how do you grow plants in a space flight with no gravity? What are the features of a system of agro-technical examples in space plantations? How do you raise plants which are used not only as sources of food, but also to regenerate water and air for the cosmonauts, so that they provide an uninterrupted replenishment of oxygen and removal of carbon dioxide in the atmosphere of the spacecraft? How do you protect the space plantation from radiation danger? How much light should the plants have, and with what periodicity? And a whole list of other no less serious questions.

How Do You Raise Plants In Space?

What does this question mean? It is really quite simple: you loosen the soil, put a certain amount of fertilizer in it, water it, put in the seed, cover it to the required depth and wait for it to grow. Seed and fertilizer we will bring on board the spacecraft from Earth, but what about soil?

In the last decades a new variety of plant-growing has appeared — "hydroponics." The word hydroponics in translation from Greek means "work with water." Originally hydroponic equipment was a watertight tub (often /38 concrete) approximately half full of a nutrient solution. In the upper part of the tub, a box with a perforated bottom was fixed. The box was filled with wood shavings or sawdust which were used as a substitute for soil: the plants were transplanted into it. Between the upper level of the nutrient solution and the perforated bottom of the box with the substrate, it is

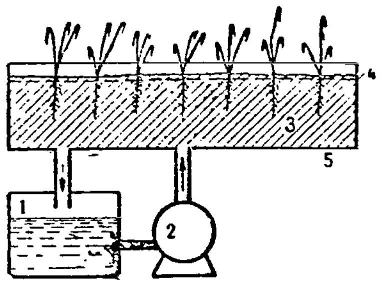

Figure 6. Plan of hydroponic growing equipment: 1 - reservoir for nutrient solution, 2 - pump, 3 - substrate, 4 - water level of substrate, 5 - growing tub.

necessary to leave free space for aeration of the roots (Figure 6). Later the entire tub was filled with some kind of chemically inert and granular material (gravel, crushed marble, coarse-grained sand, pumice, slag, volcanic tuff, vermiculite, perlite and various polymers). The nutrient solution was periodically added either from above or by flooding the substrate from below and filling the spaces between the granules. On reaching the required level, the nutrient solution was again drained into the reservoir placed below.

According to the data of the famous expert in industrial hydroponics, M. Bentley, a single square of hydroponic culture can produce 20 times more than the same sized square of ordinary agriculture.

The advantages of hydroponics include large productivity, low water expenditure, as the water in hydroponics does not escape from the root zone and soak into the soil, but drains from the tub into the reservoir and is used repeatedly. Crop quality, as a rule, is higher in hydroponics than in soil culture; the crops are cleaner. Hydroponics does not need crop rotation. Providing the plants with nutrient materials is easy to control by automation and standardization. If the hydroponic equipment is placed in a hothouse with regulated air temperature and light intensity, it is possible to plan crops quite confidently and accurately. These are the features of hydroponic plant culture that have attracted the attention of space plant-growers.

If, in fact, the crops produced by hydroponics are 20 times greater than in soil, if it is possible to manage with a limited amount of water, if the quality of the crops is better, if automation can control the system, and the harvest can be planned quite accurately by precise conditioning of basic parameters of the environment in the cultivation compartment of the spacecraft, then probably this method of raising plants would be acceptable for space.

All this is true. However, there is a serious obstacle to the use of hydroponics in space flight — the absence of gravity. On Earth, where we know very well where up is and where down is, it is very simple to flood the substrate with the nutrient solution from a tank placed above the level of the tub with the substrate. It is only necessary to open a tap in the tank. And without any difficulty after the substrate is flooded, the nutrient solution drains into the reservoir placed under it. /39

This operation, which is simple on Earth, is greatly complicated under weightless conditions. The liquid (the nutrient solution) will not run out of the tank wherever we put it. Under weightless conditions, liquid cannot be poured out of a container; it must be shaken out, sucked out, forced out. Evidently to flood the substrate in hydroponic equipment in a spacecraft, the nutrient solution must be sucked out of the tank and fed to the substrate under some pressure.

But here new difficulties arise. We know that there are solid materials which, under ordinary conditions, are moistened by liquids, as well as those which are not moistened. The first are called hydrophilic, and the second, hydrophobic. If the substrate is hydrophobic, it will not be moistened; the nutrient solution will collect in the pores in droplets. If the substrate is hydrophilic, then the liquid quickly "creeps" upward, reaches the edge, and runs over.

Removing the liquid from the substrate and pouring it back into the tank is also very complicated. It will not begin to flow. It must be sucked out; some kind of vacuum must be created. But to do this the substrate must be hermetically sealed with a cover. At the same time, the cover must have openings for the growing plants, and to pressurize an opening with a plant stem in the center is no easy task.

Thus, there are quite a few difficulties in using hydroponics under weightless conditions. Nevertheless, this method is very tempting. In a number of experiments with substrate hydroponics under terrestrial conditions, very good harvests of basic vegetables have been produced: cabbage, carrots, beets, tomatoes, etc. Harvests of 18-22 kg/m^2 were usual in the tests, and sometimes the harvest reached 30 or more kilograms.

Evidently, the search for substrates which have the most suitable properties for use in space must be continued. However, weightlessness is /40
still far from being completely understood, and many difficulties can be expected.

In recent years, in a number of countries ion-exchange resins have been used as a substrate for growing plants, especially indoor flowers. Several brands of these resins have the capability of adsorbing (absorbing) certain chemical compounds. The substrate, saturated with nutrient materials for the plants, when it is moistened with water is able to gradually, according to the needs of the plants, give the plants the previously absorbed nutrient materials. The use of such a substrate would greatly simplify the maintenance of space plantations. The necessity of preparing nutrient solutions on board the ship would be eliminated, as well as the necessity of constantly correcting it. All the work in maintaining the crops is reduced to pouring water on the substrate. All the water in the substrate will be absorbed by the plants, and will then evaporate in the process of transpiration. Such a substrate would simplify the whole life-support scheme for man in the spacecraft.

However, there will not be a complete matter cycle using this method of growing plants. Nutrient materials must be kept in reserve. But the reserve will not be in a box, but in the resins.

Up to this time, we have been considering hydroponic methods of raising plants in relation to the conditions of space flight. In weightless flight, the use of hydroponics encounters a number of difficulties. It is another matter to organize a closed biological system on the Moon or one of the planets. Although gravity on the Moon is only 1/6 of that on Earth, it is still not weightlessness. Top is top, and bottom is bottom. Liquids, as on Earth, will flow down. In short, everything is in its place. In lunar or planetary stations, hydroponics will probably be used by travellers from the Earth, just as it is by people at home on Earth. In all probability, lunar or Martian soil will be used as a substrate. This would make it easier to transport from the Earth the necessary fertilizer and materials to create a link of higher plants in the artificial matter-cycle system.

The absence of an atmosphere on the Moon makes the surface of our satellite open to meteorite showers and radiation. This will force the cosmonauts to bury the lunar station in lunar soil to protect it from meteorites and radiation. Evidently hydroponic equipment will also need to be built under a protective layer of lunar soil of appropriate thickness. It can be assumed that, to provide a vacuum seal in the lunar "dug-outs", the walls will be covered with plastic. It will then be filled with a gaseous mixture of usual "Earth" composition which would have to be brought from /41
Earth or prepared at the site.

In these surroundings, the inhabitants of the lunar or planetary station will raise Earthly vegetables: potatoes, cabbage, beets, carrots, etc.

It must be noted that hydroponics is not the only possible method of raising agricultural plants in space or on the planets.

More than fifty years ago, Russian professor, V. M. Artsikhovskiy, studying gas exchange in roots, was the first to use the "air culture" method. He proceeded from the fact that the best conditions for studying gaseous exchange in underground plant organs are created when the roots grow in moist air. From improvised materials, he constructed an apparatus in which he successfully raised peas, vetch, maize and several other plants. The basis of the apparatus was a flower pot turned upside down. The base was submerged in water. The plant was put into the hole in the bottom. The root hung down

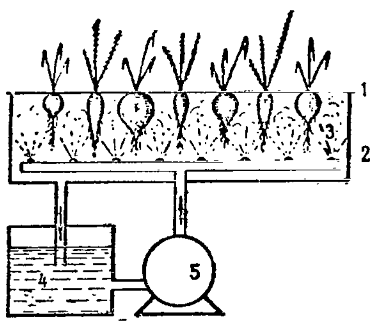

Figure 7. Plan for building an aeroponic growing device: 1 - cover for holding plants, 2 - growing tub, 3 - sprayer for the nutrient solution, 4 - reservoir for nutrient solution, 5 - pump.

inside the pot, and 6-10 times a day it was sprinkled with nutrient solution from an atomizer. For convenience in cultivating the roots, the pots were sawed into two unequal parts, the smaller serving as a door.

For many years the "air culture" method was only used in research laboratories to study questions of plant physiology. At the same time this method of plant air culture was being perfected. In the last few years this method, or as it is now called aeroponics, has become widely used on a number of farms around Moscow in raising several vegetables, as well as flowers. Aeroponics has been considerably developed in the agriculture of Bulgaria and other countries.

The basic equipment in aeroponics is a tub. The nutrient solution is fed through tubes mounted inside the tub along the walls. The tubes hold spaced atomizer jets for spraying the solution.

The unsbsorbed part of the nutrient solution runs to the bottom of the tub, and through its openings is returned to the tank with the nutrient solution. The cover on the top of the tub has openings for attaching the plants (Figure 7). The solution is sprayed for 10-20 seconds every 10-30 minutes.

Even V. M. Artsikhovskiy noted that, in raising plants by the "air culture" method, it is necessary to increase the salt concentration in the nutrient solution. As a rule, the concentration of salts in aeroponics exceeds the usual norms by 2-3 times.

One of the unquestionable advantages of aeroponics over hydroponics with a substrate is that in aeroponics the plants are not attached to the substrate; they can easily be moved from place to place. This makes it possible to use the illuminated area in the cultivation rooms of the spacecraft or the planetary station most efficiently. /42

In using the aeroponic method under weightless conditions, we can expect trouble. The nutrient solution which is not absorbed by plant roots will possibly not be returned to the tank, because under weightless conditions, liquid can collect into a ball and float in that form around the growing tub.

The behavior of liquids under weightless conditions is explained by capillary and intermolecular forces. Intermolecular forces will cause the liquid to tend to take the form of a ball — the greatest volume with the least surface. In this case, unless special measures are taken, the liquid becomes "uncontrolled."

Capillary forces do not depend on gravity, and the full extent of their activity will become apparent under weightless conditions. Liquid will move along capillary systems just as kerosene "spreads" along a lamp wick, as underground water rises to the surface, or as filter paper "removes" a drop of liquid spilled on a table.

Based on these facts, still another method of raising plants is being developed and tested which might rival hydroponics and aeroponics.

This is the so-called wick culture. The essence of this method is as follows: the cultivation tub is filled with a substrate, well wetted and holding moisture. Vermiculite or perlite are suitable for this purpose. A rope (wick) made of any kind of material which draws water well is set into the substrate. This can be a bundle of cotton threads or fabric. One (the lower) end of the wick comes outside through an opening in the bottom of the tub, and is immersed in a container where the nutrient solution is always /43
being fed. The solution is brought to the substrate by the wick and moistens it, providing the plants with moisture and nutritional elements (Figure 8).

On the basis of these same laws of molecular and capillary forces, the method of "film culture" is being developed. A porous plate, with good capillary properties, is bent at a sharp angle. The lower edges of this plate are immersed in a tub with a nutrient solution or loosely pressed into

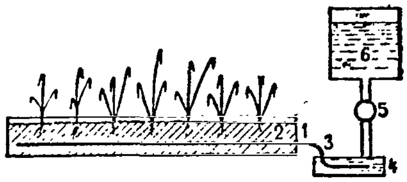

Figure 8. Plan for constructing a device for growing plants using the wick method: 1 - growing tub, 2 - substrate (hydrophilic), 3 - wick, 4 - small tank for nutrient solution, at constant level, 5 - device for automatically maintaining a constant level of nutrient solution, 6 - reservoir for nutrient solution.

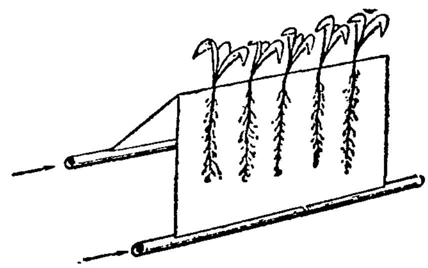

Figure 9. Plan of a device for growing plants using the film culture method.

a pipe along which the solution flows. The seedlings are placed on top, at a sharp angle, like riders on horseback. Their roots stretch along both sides of the plate. The nutrient solution is constantly being pulled along the plate, it reaches the roots, moistens them and supplies nutritional elements (Figure 9).

There is another method that is promising for use in space — the method of constant and incomplete saturation of a substrate. Usually the apparatus in this method of raising plants consists of separate containers made of transparent plastic. The size of the containers depends on the kind of plant being raised. A pipe is connected to the container. Through the pipe, a nutrient solution is constantly supplied to the substrate. The rate of supplying the solution corresponds to the rate at which the plant evaporates moisture.

This method, as well as the film culture method and the wick culture method has a common drawback. The substrate (or film) will inevitably accumulate salts from the nutrient solution which are not completely absorbed by the plant roots.

Up to the present time, a nutrient solution has not been created which would be completely absorbed by the plant as a hungry man eats up everything from the plate of food given to him. All these methods demand periodic washing of the substrates or other means of freeing them from salinization. /44

There are other methods of raising plants in space.

The methods and examples we have described for growing plants in spacecraft are being developed, perfected and tested. Before direct tests are made in space flights, it is difficult to have a preference for any one of them. Now they all seem to be rival methods. A final choice can be made only after testing these methods in space.

Green Conveyor

In closed life-support systems, higher autotrophic plants are depended upon not only to reconstruct food, but also to regenerate the atmosphere and water. Regeneration of the atmosphere — absorption of carbon dioxide and release of oxygen — is basically the work of one organ of the plant — the green leaf. The green leaf, or more acurately, the chloroplasts inside the cells of the leaf, is the only natural laboratory on Earth which accumulates solar energy, and creates organic matter. They feed, clothe and warm us, as well as release oxygen and clear the atmosphere of carbon dioxide gas.

Special demands are made on the link of higher plants in the closed area of a spacecraft: uniformity of operation, stability in time and continuous renewal of the surrounding atmosphere, as variations in the production of oxygen by green plants and freeing the atmosphere of carbon dioxide can only be within the variation limits of man's needs. A man at rest (sleeping) uses less oxygen than when he is awake or working actively. These variations are usually 15-20% of the average hourly gas exchange level of man.

It follows that the leaf surface in the link of higher plants must be as stable as possible in time. Consequently, in a spacecraft or at a planetary station all the plants must not be planted at the same time, nor harvested at the same time. Thus, the usual means of farming on Earth are unacceptable in space, because it does not provide uniform and continuous /45 regeneration of the atmosphere in the spacecraft or in the planetary station. It is necessary to find another means of growing plants for space, one which would provide a stable total area of green leaves in the space plantation.

And the limited space in the spacecraft or planetary station, as well as the complexity of bringing light energy into the cultivating room and removing heat energy from the system, make it necessary to find a way to use the illuminated growing area most efficiently and intensively. The minimum growing area must provide maximum food, water and oxygen.

All these features of plant-growing in space have forced researchers to develop special means of growing plants, which have been named a green conveyor.

This term first appeared in cattle-raising, where cattle-breeding farms began to grow fast-growing green forage, calculated so that during the whole summer it would be possible to mow grass daily and feed the animals on certain sections of these fields.

Somewhat later, cattle breeders began to be concerned about feeding the animals in the winter months with food greens containing vitamins. With this in view, 7-10-day seedlings of cereal plants (oats, barley) are continuously cultivated and fed to the animals.

A number of devices for continuous (conveyor) cultivation of green forage /46 have been developed and patented (Figure 10).

Basic to the construction of such a conveyor is a transporter with an infinite belt and a mesh bottom. At the start of the conveyor, there is a

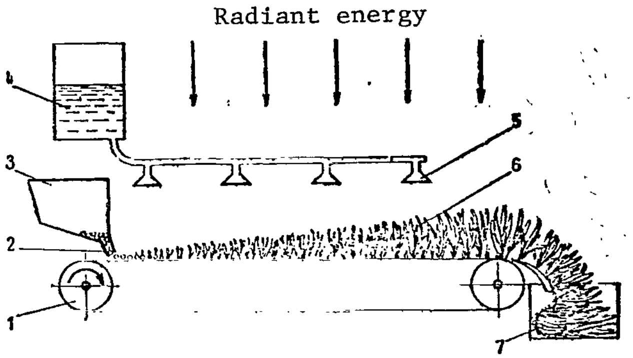

Figure 10. Plan for constructing one of the devices for growing green feed on a conveyor: 1 - mechanism for moving the conveyor, 2 - sowing device, 3 - reservoir, 4 - reservoir for nutrient solution, 5 - sprinklers, 6 - growing plants, 7 - finished product.

device for sowing seed. Along the conveyor, over the transporter, lamps and sprinklers are mounted. At the end of the conveyor — a basket for removing the produce.

The speed at which the conveyor moves is such that it makes its way from beginning to the end of the device in 7-10 days, which it takes to produce green sprouts. A continuous green brush of green sprouts is removed from the conveyor. Usually the roots of the sprouts are closely entangled together and a continuous green "rug" comes off the conveyor. After being washed with water these "rugs" are fed whole to the animals.

In this kind of device, a kilogram of seed is transformed into 4-5 kg of green vitamin food.

Planting seed every day at one end of the conveyor, the crops can be removed at the other. This is the way green feed is continuously produced on some cattle-breeding farms.

A similar means of operating a conveyor would fulfill one of the necessary conditions of raising plants in space plantations, namely continuity. But we must still be concerned with the intensive use of the entire illuminated area in a closed space.

We know that a number of agricultural plants have for a long time in all areas been raised by the transplanting method. The use of this method has two purposes. The first (especially in northern regions) is to lengthen the growing period. The seedling is grown in a hothouse or under glass when the air has not yet warmed up, and plants cannot grow without protection. But the transplanting method is also used in southern regions where summer is long enough for early production.

And the transplanting method makes efficient use of the growing area.

The most typical plant which is grown by the transplanting method is cabbage. Cabbage seedlings up to the 10th day of growth need 1 cm^2 of growing area for one plant; 30-35-day seedlings need 25 cm^2. One mature plant of early cabbage needs about 2000 cm^2, medium ripening — 4000 cm^2, and late ripening — 5000 cm^2.

Therefore, the necessary planting area for one cabbage plant during the growing period changes between 2000-5000 times, depending on the variety. /47
Evidently, it is inefficient to sow and right away take up the whole area needed for mature cabbage with the small plants. Therefore, even in southern regions with sufficiently long growing period they usually resort to using the seedling method. While the seedlings are being readied in small sections of the garden, the rest of the land is being used for another kind of crop. It is reasonable that early cabbage for the first two months of growth "uses" only 30% of the area it needs to mature; medium ripening varieties in this period of development "use" 15% of the area, and late ripening varieties — only 7%.

These considerations are taken into account in developing plans for conveyor growth of plants in space.

Two principles can be assumed as the basis of the conveyor plans being developed, depending on the method chosen for growing plants: growing plants using a substrate and growing plants without a substrate (aeroponics or another variety of the substrateless method without fixing the plant roots). We must note that the possibilities for a conveyor in the substrateless method of raising plants are wider and more favorable.

In the substrate method of growing plants, they are firmly anchored by their roots in one place (as in growing in soil) and their free movement during growth is impossible. Therefore, the conveyor in the substrate method of growing plants can be organized the same way it is on livestock farms. The growing area set aside for a particular plant is divided into individual squares in conformity with the length of the growing period of the given plants, and the accepted frequency of crop removal and planting. This frequency of removal has received the name "conveyor step."

Let us suppose that we need to organize a conveyor of radishes. Radishes are a quick-ripening crop, and most varieties produce a harvest after 30 days of growth. We will assume that the conveyor step is set at 3 days. In this case it is necessary to divide the growing area into 10 squares (30:3=10). Each square must be seeded 3 days after the preceding one. Thus, in 30 days all the squares will be sown; in all squares will be plants of various ages and in the first square crops can be removed. The conveyor reaches a plateau and begins to function normally. In the whole growing area, leaf surfaces of various maturity are developed in the plants, which regenerate the atmosphere and water.

Beginning with the 31st day, the crops are removed by squares. The /48
square freed from crops is reseeded the same day..., etc.

The leaf surface of such a "field" is practically constant. Its variations, evidently, will be within the limits of those taken away with the harvest of the next square in turn every three days as well, as within the limits of individual plant variability.

A conveyor with other cultures is calculated analogously to the example with radishes.

This kind of conveyor provides a continuous removal of produce and little-changing leaf surface. But it does not provide the most efficient use of the illuminated (seeded) area. With the substrate method of growing plants, there is hardly a more perfect conveyor organization possible.

The possibilities of organizing an efficient conveyor in the substrateless method of raising plants are much greater. In that case plants can be moved along the growing area, because their root systems hang in the air and are only sprinkled periodically with the solution.

In the substrateless method of growing plants, it is possible to organize the conveyor so that practically all the illuminated area will be equally and maximally used. This is practicable if the plants are moved to a new place every day, and the seeds (or the sprouts, whichever is more convenient and advantageous) are planted as close together as possible and — as the plants grow — they are separated farther and farther apart.

Designers have developed a number of versions of planting covers for the growing tanks which would allow the plants to be placed farther apart according to their size. One of the possible versions of a planting cover is diagrammed in Figure 11.

The seedlings are placed in slots for the plants in special pockets. The pockets move freely along the slots, arranged in diverging rays. This provides increasing distance between the rows. In the first period of growth, while the plants are small, the pockets are close together. Later, the distances between them are increased to the optimum distance for each kind of plant.

Thus, the distances between plants in a row are changed by moving the /49
planting pockets along the slot. And the distances between the rows are changed, because the slots are arranged in diverging rays.

In arranging a conveyor by this method it becomes possible to form and maintain an optimum growing pattern with optimum leaf area over the whole planting area.

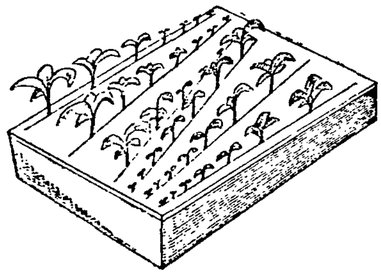

Figure 11. One of the possible plans for constructing a cover for conveyor growing of plants without a substrate in diverging slots.

There are a number of other plans for planting platforms to use effeciently the illuminated area in the cultivation room of the spacecraft.

Biologists have very thoroughly studied the question of how many leaves it is feasible to have in one growing area, so that the basic working organ of the plant — the leaf — can carry out photosynthesis normally. Usually the leaf area of all the plants in a given area is determined. The ratio of leaf area to planting area is called the leaf index.

It has been established that the optimum leaf index of a planting varies within wide limits, and depends on the intensity and quality of the light. Thus, in growing plants using incandescent lamps with a total strength of about 150 W per 1 m^2, the optimum leaf index would usually be 7-8, i.e., the leaf area of all the plants would be 7-8 times greater than the area of planting. If these plants are grown in light from xenon lamps, then the optimum leaf index will be lower. In other words, in illumination of plants with xenon light, the upper layer of leaves uses the radiant energy more in- /50
tensively, absorbs it better, and nothing reaches the lower leaves.

A conveyor with moving plants can and should be built so that in the entire planting area an optimum leaf index is maintained at all times. Tests show that this can be done in nearly the entire area. The exception is just the beginning of the conveyor with the smallest plants which have not yet developed a sufficient number of leaves.

It is easy to imagine that movement of the plants during their growth would not be steady, but must correspond to the growth curve of the underground

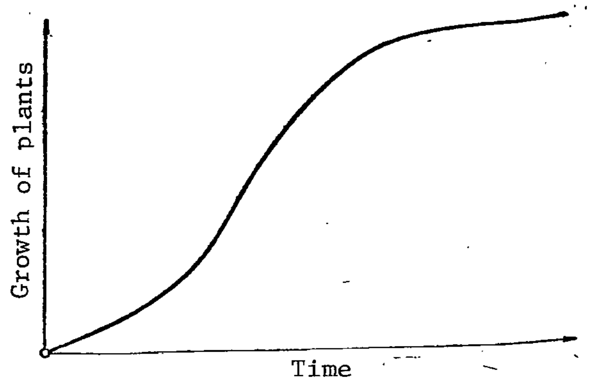

Figure 12. Typical growth curve of plants.

part of the plants. A typical growth curve for vegetable plants is given in Figure 12.

Thus, to provide cosmonauts or inhabitants of planetary stations with steady food, air, and water, it is necessary to organize a conveyor for growing all the plants in the space plantations. The growing area in cultivation rooms can be used most efficiently by growing plants without a substrate. In this case of conveyor arrangement, an optimum growing pattern is feasible in nearly the whole cultivation area.

Biological Compatibility

Every living organism, be it plant, animal or man, is continuously exchanging matter with the environment in the life process. In the process of exchange of matter, something enters the living organism from the environment, and something is released.

The withdrawal of matter from the environment and releasing of various excretions (metabolites) from the organism into the environment has an effect on the environment. It changes as a result of the vital processes of its inhabitants. This influence of living organisms on the environment, in most cases, also affects other species living in the same conditions.

The mutual influence of organisms living in the same conditions can be favorable, and contribute to increased growth and development of the organism. But more often this influence is unfavorable, and acts oppressively on species living together.

From time immemorial, farmers have known that various plants growing in one plot have a mutual effect on each other. Some kinds readily and with mutual help get along well together side by side. For example, foresters /51 know that firs and larches make a good forestation. Oaks and lindens get along well together, and have a beneficial effect on each other. Other species oppress each other and cannot create a rich forest. Examples are the interrelation of oaks and ash trees, oaks and white acacias, or pines and red elders.

Agriculturalists know just as many examples of the positive and negative mutual influence of plants. Thus, combined plantings of vetch and oats are an example of the favorable co-existence of two species. Peas and vetch coexist somewhat less well, and peas do not get along at all with maize.

The many problems of the mutual effect of growing organisms can be divided into two large groups.

The first of these includes problems of the joint use of basic factors of the environment which are necessary for good growth of the plant. We mean: light, elements of root nutrition, moisture, carbon dioxide — in other words, it is a question of the plants growing together fighting for the basic factors of growth. For the problem we are considering — creating a closed ecological system in space flight or planetary station conditions — this group of problems is of secondary importance. In high-intensity cultivation of plants in a limited growing area, in the cultivation room of the spacecraft or planetary station man can provide a constant supply of all the nutrient materials, moisture, and radiant energy that the plants need in optimum quantities.

The second group of problems includes problems of the mutual effect growing organisms have on each other through the products of their vital processes, released by roots and leaves.

Biological science has accumulated a large amount of data which indicate that in the life process plants release into the surrounding medium various physiologically active materials (mineral and organic), which affect other organisms.

Around each plant a distinctive microworld is created which is dependent on the presence of plant excretions. First of all, there are its ordinary excretions: guttation (or plant "tears"), nectar, root excretions; secondly, excretions appearing when the plant is injured. These include phytoncides, honeydew, gums, Thirdly, a number of substances excreted from leaves and stalks of plants when they are watered. The substances washed off by precipitation are primarily mineral salts.

Several dozen different active substances in plant excretions have been /52
found and defined in the last decades. The number of excretions under study continues to increase. They include organic acids, amino acids, unsaturated aromatic acids (including caffetannic, cinnamic, ferulic, etc.), aldehydes, unsaturated lactones, dihydroacetic acid, inolylacetic acid, various flavones and many others.

At the present time we do not know the chemical composition of many excretions. Work is still being continued. However, the exceptional importance of this aspect of the plant activity is evident. It is especially important for closed cultivation rooms in spacecraft or planetary stations.

According to the calculations of some scientists, the annual production of all plant excretions is dozens of centners (100 kg) per hectare (2.47 acres) of vegetation. In other words, excretions are approximately equal to posthumous plant residue in a given area.

Under ordinary Earth conditions, we very often do not notice and are not aware of the various plant excretions. This can be explained first of all by the fact that in the majority of cases their quantity at any one time is comparatively small; secondly, plant excretions begin to interact with the environment slowly (they decompose in light; they are oxidized). They are absorbed by the soil or by other plants, or the microbic environment of the plants. In their interaction with the soil, with plants, or microbes the plant excretions have an effect on them which is apparent as growth suppression, lower harvest, etc. Finally, thirdly, constant ventilation, circulation of the atmosphere, the air blowing, quickly carries away and dissipates into space light plant excretions. However, the smell of flowers, of needles in the forest, of potatoes or tomatoes in the fields and of other kinds of plants are well known to us. All these smells correspond to plant excretions. At the present time, the study of plant excretions and their effect on the environment and on other kinds of plants growing together with them has expanded and developed into a whole new direction called allelopathy.

Allelopathy studies the physiologically active substances and their cycle in biogeogenesis. Among the most important problems which allelopathy is studying are the following:

accumulation and excretion by plants of physiologically active substances;

accumulation and transformation of substances in the environment;

absorption and effect of physiologically active substances on other plants.

All these questions are very important in the creation of a closed cycle /53 of matter in an artificial ecological system. However, in relation to space problems, the list of the most important problems of allelopathy is incomplete. It does not include the effect of physiologically active plant excretions on man.

An artificial matter-cycle system using a link of higher plants as a biological regenerator of food, water, and air is created for the sake of man's safety in space flight. Therefore, in studying the allelopathic effect of plants on the environment, it is, first of all, necessary to evaluate the effect of plants on man.

All that has been discussed in this chapter can be defined by the comparatively new concept in biology — "biological compatibility." This term designates the possibility for various organisms (be they plants, animals, or man) to develop satisfactorily without damage to their vital activity, life, work or growth in one closed space with a common atmosphere.

In this field, everything has not been explained. Intensive research is necessary which would provide answers to these questions:

a) what kinds of higher plants will not be mutually oppressed in closed cycles?

b) how will the environment (especially the atmosphere) be changed in closed spaces of the spacecraft or planetary station as a result of prolonged cultivation of a collection of plants? What substances can accumulate in them; what kind of an effect do they have on man; what is the highest safe concentration of these substances?

c) development of means to absorb accumulating physiologically active substances, their destruction, and the return to the cycle of chemical elements in them.

There is much work yet to perform on these questions.

Radiation Danger in Space and Ways to Eliminate It

A serious obstacle in man's penetration into space is ionizing cosmic radiation. This creates additional difficulties and holds great danger for higher plants which must accompany man on his space journies.

Cosmic radiation was discovered at the beginning of the century, but there has been a systematic study of it only in the last 10-15 years when /54 sensitive and reliable dosimetric equipment has been developed and rockets and satellites have made it possible to penetrate far enough into outer space to obtain more complete information.

According to current ideas, ionizing radiation in outer space comes from three sources. The first of them is the Earth's radiation belts. They were formed as a result of incoming charged particles from outer space and from the Sun being trapped by the Earth's magnetic field. Scientists distinguish three belts of charged particles around the Earth. The most dangerous is the inner one, which covers the regions around the equator and extends almost to the polar latitudes. The edge of the inner belt of charged particles closest to the Earth is measured at various altitudes. At places, the ionized belt approaches the Earth in tongues; at other places it moves away from it. This depends on the phase of solar activity.

In the eastern hemisphere, the lower edge of the radioactive belt is about 1500 km from the surface of the Earth. In the western hemisphere, it is only 500 km. This inequality is explained by the variance in the magnetic and geographic poles of the Earth.

The outer radiation belt extends to 70-150 thousand km from the Earth. The Earth's radiation belts are mostly composed of protons and electrons.

Radiation intensity in the zone near the Earth is so great that to penetrate it or even to cross it at cosmic speeds is dangerous for living beings without special protection. But it is possible to reach deep space, beyond the limits of the radiation belts around the Earth, if correct space trajectories are selected. In the regions around the poles (arctic and antarctic), radiation belts are practically absent, and an exit to outer space through the polar regions is safe. Orbit around the Earth at altitudes less than 500 km will also be outside the radiation belts. Flights along this route are not dangerous if they do not coincide with solar (chromospheric) flares.

Chromospheric flares are the second source of cosmic radiation.

The Sun is a gigantic incandescent sphere where complex physical and chemical processes are constantly occurring. It more or less regularly ejects from its depths powerful streams of high energy particles. Fluxes of these particles are directed on all sides. They principally carry protons (about 85%), and alpha-particles. Observations have established the definite periodicity of solar activity. Maximum activity of solar flares is observed, as a rule, every 11 years. The greatest activity of the Sun usually coincides /55 with the appearance of dark spots on it. Then the period of the "quiet Sun" appears.

Solar flares, especially in the active solar period, are so strong that they are 100-200 times greater than the radiation tolerance of living organisms. Therefore, it would be very important to discover a method for predicting solar flares. Encouraging results in this direction have been obtained by the studies of the outstanding Russian scientist, A. L. Chizhevskiy. He began his research in 1915 and established that certain microorganisms respond very sensitively to solar activity. In a number of cases, certain bacteria begin to behave differently 4-5 days before instrument observations can determine solar activity. Consequently, it might be possible to create a unique "living barometer" to predict the behavior of the Sun and to warn men in space about the threat of danger. The cosmonaut would thus receive a signal ahead of time about the threatening danger, and have time to take protective measures.

Other methods of predicting and warning men of radiation conditions in space are also being developed.

Finally, the third source of cosmic radiaiton is primary or galactic cosmic radiation. Galactic cosmic radiation has the most diverse particles:

protons, alpha-particles, as well as multiply charged ions of heavy metals. Its intensity is more or less constant at about 20 rad per year. The majority of living organisms can tolerate radiation of this intensity without particular danger to their life. Plants whose growing period seldom exceeds 3 months would receive only 6-7 rad, which would present no danger for them. In some cases, this level of radiation could stimulate plant development.

Thus, the greatest threat for space plantations are solar flares which, by sudden and powerful radiation, could put the greenhouse out of service.

What dosages of radiation can plants tolerate?

We know that small dosages of radiation cause stimulation of plant development. Medium dosage retards development, and strong dosage kills. The amounts of weak, medium and strong dosages for living organisms is not well known.

We know that great differences in resistance are observed among organisms. Pitch pine (Pinus rigida) is the least resistant. It will die in six months /56
under radiation of only 2 roentgen units a day. Sage is very resistant. Radiation up to 350 roentgen units a day does not cause any damage. There are algae and fungi which can withstand several thousand roentgen units a day. We know that dormant seeds are much more resistant than growing plants.

The most widely-distributed garden plants which are of primary interest for space plantations include: potatoes (tubers) and beans; beets and lettuce must be included in the least resistant species. Thus, in irradiating tuberous potatoes with dosages of 4000 rad only a few potatoes germinated. Stimulation of development in potatoes is observed at dosages of 500-1000 rad. Seeds of the potato plant were by one order of magnitude (10 times) more resistant and their death was observed in irradiation of about 40,000 rad.

Significant differences in the radioresistance of different varieties of plants have been established. Seeds, as well as sprouts of cabbage plants and radishes, are much hardier in comparison with the above-named plants. Thus, the germinating ability of cabbage seeds, after being irradiated with 500 thousand rad, is lowered only 5% in comparison with nonirradiated seeds.

Irradiation with protons has approximately twice as strong an effect as irradiation with gamma-particles.

From this information alone, it becomes clear that chromospheric flares are a serious danger for space gardens.

Evidently it is not possible to provide strong protection from radiation penetration in the form of massive lead covers or concrete shelters on the spacecraft. But there are other methods which could help safeguard plantings on the craft from the destructive effect of radiation.

Scientists are working persistently on this. Gradually three promising trends have begun to appear:

First — the use of certain chemical compounds, which increase plant radioresistance;

Second — it was found that living organisms increase their resistance 3-4 times when they are placed in an oxygen-free medium. It is theoretically possible, having received a warning about a flare on the Sun, to purge the atmosphere of the space hot-house with air devoid of oxygen;

Third — we have mentioned that the magnetic field around the Earth blocks the flow of cosmic radiation. The question has arisen of creating a magnetic field of the necessary strength around the ship which would protect it from radiation penetration, just as the Earth's magnetic field guards our planet.

All these seem promising and could succeed in solving the problem of reliable protection of spacecraft from the destructive effect of radiation.

This problem is very acute, not only for plants, but also for man. In fact, man tolerates much smaller dosages of radiation than plants. Work is being conducted in this direction. For the present, the route and time of space flights are selected cautiously, in relation to the state of the Sun. Solar survey can still give a great deal of information for predicting radiation conditions in space. We must also not forget about the genetic effect of radiation. But that is a separate subject. /57

This is the situation with radiation danger in space.

The Moon — the first object which will probably be inhabited by man — has no atmosphere and has only a very low-power magnetic field. Therefore, the lunar surface is not protected from penetrating radiation coming from outer space. Evidently, in conquering the Moon and building permanent stations there with a life-support system where a link of higher plants will be used, the simplest means of protecting lunar plantations from penetrating radiation would be lunar soil. At a sufficient depth "underground" pressurized rooms will be built, filled with air brought from Earth. And only after that will planting take place.

Control of the Link of Higher Plants

In the chapter on modeling nature, we said that normal operation of the whole artificial system of the cycle of matter is possible only when individual links of the system work in harmony with sufficiently stable "entrance" and "exit" of all the elements of each link. The balancing of matter in the system's cycle demands strict control and regulation of movement between the links. And this presupposes reliable and stable operation of each link. Otherwise, it is inevitable that the cycle will become unbalanced.

Therefore, each link in the system must work exactly "like a clock". In particular, the link of higher plants must at the necessary time and at a certain rate provide the system with oxygen, water, and food and absorb a certain amount of carbon dioxide from the atmosphere and mineral salts from the nutrient solution.

This kind of efficient operation of the system can only occur in the normal activity of the plants which provide necessary products and utilize processed wastes of man. But the normal activity of plants is only possible /58 at the optimum level and combination of all factors of the external environment. Therefore, continuous control of environmental factors and their regulation is necessary. In other words, the parameters of the medium in which the plants are developing must be controlled. It is also necessary to control the intensity of basic physiological processes in the plants and to regulate these processes. This also relates to the field of control.

Thus, environmental factors of plant development (intensity, spectral composition and duration of light, air temperature, its moisture, composition of nutrient solution, etc.), the occurrence and intensity of the most important physiological processes in plants of different ages and varieties grown in the link of higher plants (transpiration, photosynthesis, absorption of elements of root nutrition) represent a single system. This system is very complex and dynamic; it is subject to variations. It is enough to change only one of the many environmental factors or the intensity of any of the physiological processes, and the operation of the whole system will be disturbed. Let us assume the temperature of the environment is lowered. This will affect the relative humidity of the air — it increases. Temperature change also affects the absorption of mineral nutrient elements; their rate of absorption is changed and the ratio of the elements.

The altered quantity of absorbed nutrient elements affects the course of photosynthesis, because the plants will have a different quantity and a different qualitative composition of material available for the formation of matter. An increase of relative humidity of the air inevitably entails a reduction of transpiration. Thus, a change in only one parameter of the environment causes a "chain" reaction and affects an entire set of other parameters of the environment and the vital activity of the plants. As a result, the operation of the whole link is disturbed and, just like along a chain, it is transferred to other links in the closed cycle of matter.

It follows that each link (and the whole system) must be controlled. It must be controlled to provide the continuous combination of those environmental factors which are optimum for the course of physiological processes in the plants. Only in this case will the "entrance" and "exit" of the link be stable.

In the last two decades a whole new science about system control has arisen — cybernetics.

The basic control of any system in the regulation of its parameters. /59
For this, it is necessary to obtain information from the regulated object on the condition of the parameter which is to be regulated. The information obtained about the state of the controlled factor must be compared with normal characteristics. Then, by using a control device in the controlled system, a command is sent which corresponds to the necessary action to bring a given parameter back to normal.

All the units necessary to obtain information from the controlled object, to process it, to compare it with normal, sending commands to control the parameters deviating from normal, and the use of this command are combined in the general term — automatic control system. Figure 13 gives the general outline of a cybernetic automatic control system.

One of the most important details of any automatic control system is the data unit — a device for obtaining information about the condition of the parameter which is to be regulated.

Certain requirements are imposed on data units. First of all, the data unit must be absolutely harmless to the plants. For example, to obtain information on leaf temperatures, a data unit in the form of a needle which

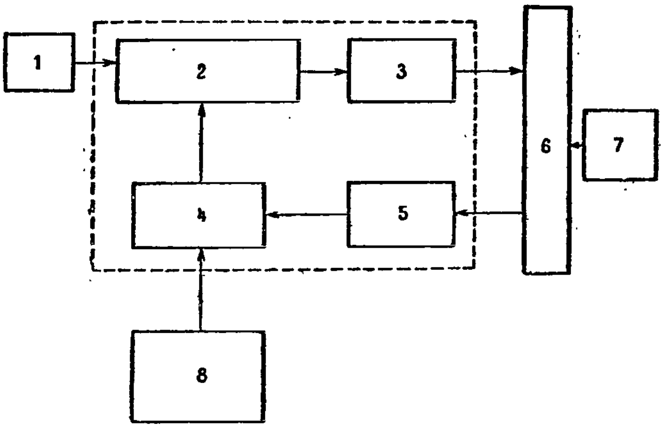

Figure 13. Basic plan of an automatic control system: 1 - power unit, 2 - transducer and signal amplifier, 3 - slave mechanism, 4 - equalizer, 5 - measuring device, 6 - controlled system, 7 - external action disturbing operation of the system, 8 - data unit (program).

is inserted inside the leaf is often used. The leaf is inevitably wounded and, as a consequence, the information is distorted. /60

Plant growth is quite a long process often lasting several months. Information must be continuous and prolonged in order to regulate growth processes of the plants during the entire growing period. And for conveyor growing of plants, there is still more prolonged work necessary in obtaining information.

Plant growth is not determined by any single factor of the environment, but by a whole complex of them. It is just as difficult to judge the condition of a plant by any one physiological characteristic. For reliable control of the vital activity of an association of plants, simultaneous information about various environmental factors and about the course of various physiological processes is necessary.

It must be noted that in the arsenal of biological cybernetics there is still not a sufficient collection of reliably and long-operating data units to provide the necessary information about the condition of environmental factors and the vital activity of plants.

Among the first successes in this field, we must mention a number of developments made at the Agricultural-Physical Institute VASKhNIL. These instruments operate satisfactorily and provide information on several parameters. We must note the microthermometer, attached to the plant leaf without damaging it; the microhygrometer, which makes it possible to obtain information about the relative humidity of the air in direct contact with the leaf; the micro-data unit for recording movements of liquid through the plant; the concentration meter which controls the general concentration of salts in the nutrient solution, and several others.

The first steps have been taken, but there are an endless number yet to be made. For example, control of the total salt concentration in the nutrient solution cannot give information about unbalanced absorption by the plant of individual components of the nutrient solution. At the same time, a disturbance of the optimum ratio of salts in the solution could react negatively on the condition of the plants. Data units must be created which will reliably record the plants' use of basic nutrient elements.

Conclusions

The beginning of the space age in the history of man demands new research, the development of new disciplines in the various sciences. Space physiology of man and animals is being developed, as well as space medicine, /61
space radiology, etc.

Creating closed life-support systems makes new demands on plant physiology, which, as K. A. Timiryazev noted, is the basis of efficient agriculture. A need has arisen for studying the behavior of plants placed in closed, pressurized spaces. Already the first observations on the development of plants in such conditions have yielded a number of new and somewhat unexpected facts. In determining the intensity of photosynthesis in pressurized areas, it has been shown that higher plants are quite sensitive to increased oxygen in the atmosphere. A concentration of this gas in the air of 24-25% (it is 21% in the normal Earth atmosphere) is sufficient to greatly reduce the intensity of photosynthesis. On the other hand, if partial pressure of oxygen in an air-tight chamber is decreased below its usual concentration, this stimulates plant growth and intensifies photosynthesis.

First observations on the assimilation coefficient of plants in dynamics indicates that this characteristic is by no means stable in time, but changes very greatly in 24 hours.

Undoubtedly, there is much yet to be revealed on the question of the excretion of physiologically active substances by plants and their significance in the life of organisms.

We have every reason to expect new information on the questions of mineral nutrition in raising plants without a substrate in the prolonged use of fixed nutrient solutions and in constant conveyor growth of plants of different ages.

An almost completely unknown field until this time is the reaction of higher plants to weightless conditions. Probably the first of these physiological experiments with growing plants in space will yield new and unexpected information.

These, and a whole list of other questions on the vital activity of plants in space flight, in planetary stations or even simply on their prolonged growth in pressurized areas, will undoubtedly open up a new chapter in plant physiology which we have every justification for calling space plant physiology.

Important new steps in mastering space have been made while this book was being written.

The flights of spacecraft Venera-2, Venera-3 and Venera-4 have been made. A scientific station was placed in lunar orbit which for nearly four months transmitted information about our closest neighbor. Valuable biological data were obtained from the flight of spacecraft "Kosmos-110" with two dogs on board. /62

It is evident that Soviet successes in soft landing on the Moon and on Venus, in docking and undocking automatic systems in space, are revealing great future prospects for the study of the planets, satellites, and asteroids in the solar system.

The time is drawing near when what has been described in this book will be transferred from the laboratory and Earth-bound models and used on board a spacecraft. A cycle of matter will be established in an artificial system in which higher photosynthesizing plants will play a basic role as a regenerator of food, water and air to ensure normal living conditions for the courageous conquerors of space.

The role of plants in space, of which K. A. Timiryazev spoke in his time, is becoming wider and richer.

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Translated for National Aeronautics and Space Administration under Contract NASw 2035 by SCITRAN, P. O. Box 5456, Santa Barbara, California 93108.

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